FRONTISPIECE.—More than 75,000 ft. of gaseous-tube lighting in various colors—red, gold, blue, green, and purple—were employed in the illumination effects of Chicago's Century of Progress Exposition. (*Courtesy of Electronics.*)

ELECTRONS AT WORK

A SIMPLE AND GENERAL TREATISE ON ELECTRONIC DEVICES, THEIR CIRCUITS, AND INDUSTRIAL USES

BY

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FIRST EDITION
SEVENTH IMPRESSION

McGRAW-HILL BOOK COMPANY, INC.
NEW YORK AND LONDON
1933

PRINTED IN THE UNITED STATES OF AMERICA

THE MAPLE PRESS COMPANY, YORK, PA.

PREFACE

We are living in the electronic age. Millions of electronic devices already are at work. Electronic tubes increasingly control the machines of industry. The electric eye, with its associated electronic tubes and apparatus, is rapidly replacing the human eye in many branches of industry where it has a great many invaluable applications, a number of which are described in this book. Inspecting and sorting a carload of beans a day, thereby replacing many human eyes and fingers, make just one job for electric eyes and electromagnetic fingers. Robots or electric servants are the order of the electronic age. So important has the subject become that a great journal, frequently referred to in the following pages, is wholly devoted to it.

This book is intended as a guide to those who desire a general knowledge of the subject of electronics. The index is purposely arranged for use as a glossary-guide for reference in connection with terms and their meanings. A list of the applications of electronics is given at the beginning of the first chapter. Fundamental quantities, beginning with the known components of matter and energy; electric potential or voltage; ions and electrolysis; charging bodies; dielectrics; electric condensers; magnetic and electromagnetic phenomena; oscillations; vacuum tubes; gaseous-discharge lamps and tubes, and photoelectric cells, their circuits and uses; cathode-ray tubes, invisible light, x-rays; alpha, beta, and gamma rays, cosmic rays, neutrons, positrons, deutons, and the artificial disintegration and synthesis of matter—all are treated, and their various applications to industry and biology are discussed.

This book aims to give a clear insight into the fundamentals of electronics as well as to present its practical applications. The text is written in a semipopular manner so that it may be easily read and understood. Mathematics and complex circuits are for the most part avoided. An important principle adhered to throughout the text is to emphasize principles and applications as much as practicable rather than to show types of apparatus that undoubtedly will be improved upon and thus become obso-

lete. Fundamental principles do not change so quickly, although there may be different explanations for them.

Theories are word or symbolic pictures drawn to explain apparent facts, but it should be recalled that nobody knows what reality is and that theories change as new apparent facts are brought to light. Scientists are not concerned with dogma. It is with this understanding that explanations are made in this volume, where the simpler general theory is employed when it will give the reader a mental picture of how a phenomenon apparently works. Often such theories have little value except as modes of explanation.

Regardless of how simple a structure may be when completed, it should have a good foundation. Consequently, the first few chapters treat fundamentals with more attention to relationships than will generally be found throughout the rest of the text. The first chapter, especially, is intended as a convenient place of reference for the meanings of terms and abbreviations, and for fundamental information.

Somewhat general information regarding electronic devices and apparatus is given because there are so many types and circuits, many of which are patented, and because the art is developing so rapidly, but many specific circuits and types of apparatus are shown and described. Descriptions of electromagnetic and other devices used with electronic apparatus are avoided as much as possible. Associated mechanisms are not electronic in nature and hence have no place in this volume. The book "Magnets" shows many switching, controlling, protective, and other electromagnetic devices for use with electronic tubes and circuits. All details may be obtained from manufacturers of standard apparatus, and these should be the final guides.

Much of the information regarding the practical applications of electronic devices and specific details has been gleaned from such publications as *Electronics*, *General Electric Review*, *Electrical Engineering*, and *Electrical World*, as well as from various digests, while information of a more scientific nature has been obtained from various works, the more up-to-date information being found in *Science News Letter*, *Science*, and other publications of the scientific societies, the debt to all of these sources being acknowledged with full appreciation.

One object of this book is to enable the reader to understand the excellent articles on new electronic devices and apparatus

appearing in various publications. Having once obtained a general knowledge of electronics, the articles can be read with understanding and thus one can keep up to date. Since much may be learned from history, the historical development also is included in many instances.

No assumption has been made that all readers will read this book through from cover to cover. Many will read only portions of especial interest to them. Therefore, although cross references are used to some extent, there has been no hesitancy in making repetitions, as may be noted by one who reads the entire book. The book aims to take the mystery out of electronics. The fundamental principles are simple enough—though they must be studied in order to be understood—and the text has been written with an endeavor to spare the reader as much effort as possible. Any one wishing to obtain only a general idea may read the book without close attention to the relations of fundamental quantities.

Manufacturing executives can here learn how electronic devices may be used to improve processes, increase production, and, therefore, effect saving. Much mechanical equipment is bound to be junked as improvements are made, just as the electric drive dispensed with cumbersome shafting. Plant engineers and electricians will find many useful applications of electronic devices when they become more familiar with the principles and the uses to which they already have been put. Students will here find a general outline of the subject, the more intimate details of which are given in their textbooks and other publications and will thus obtain a grasp of the entire subject which should aid them in their studies. The general reader interested in the relatively simple means that are destined to bring about a vast industrial revolution, with its resultant effects on our social system, will find the answer through a casual reading of only parts of the text.

There are tremendous possibilities in every field of endeavor for all electronic devices in various forms. The electronic art presents golden opportunities.

The text tells why and how. "How much" is omitted to some extent, largely because of units, since "why" and "how" are the principal features.

Because of the very general nature of this volume and the fact that the information contained in a single article may have been

obtained from several sources, as well as from the author's own experience, references are not given so freely as might be desired, but full acknowledgment of indebtedness is made.

The index to a volume often may be profitably studied. A reader should experience no difficulty in referring back to some portion of the book after it has been read. Credit is due the author's wife, Ella H. Underhill, for her valuable assistance in this connection.

CHARLES R. UNDERHILL.

September, 1933.

CONTENTS

ELECTRONS AT WORK

CHAPTER I

INTRODUCTORY

As defined by the journal *Electronics*, this subject deals with electronic tubes and their radio, audio, visio, industrial and general applications, as in broadcasting, telephony, telegraphy, beam transmission, beacons, aviation, receivers, carrier systems, amplifiers, compasses, musical instruments, electric recording, photoelectric cells, television, sound pictures, traffic control, crime detection, power transmission, voltage regulation, metering, train control, automatic processing, measurements, machine control, counting, grading, chemistry, metallurgy, therapeutics, surgery, and so forth. Vast quantities of electronic tubes are employed in telephony alone. While it is not the purpose of this volume to describe all of the above apparatus, it is the purpose to describe the electronic devices entering into such systems and applications. Some of the characteristics of the electron are outlined in the present chapter, but since electrons are one of the kinds of building blocks of atoms and since the latter play important parts in electronics, matter briefly is discussed first. This chapter will be found a convenient source of reference as to units and quantities mentioned throughout the volume.

1. Matter is anything that has weight. Weight is the pull of gravity between two bodies of matter, as between a rock and the earth. Hence weight is a force. Inertia is that property of matter which causes it to persist in its state of rest or of uniform motion unless some force changes that state. As used in engineering and physics, the term *mass* means the measure or expression of quantity of matter in a body, indicated either by its weight or by the amount of force necessary to overcome its inertia in speeding up or accelerating the body, as from a state of rest to a given speed or velocity in a given time.

Matter contains *energy*, of which force is a manifestation. Whenever there is a store of energy which may be expended by

moving a body, a force always is in evidence. The two general kinds of energy are potential energy and kinetic energy. A suspended body contains a store of potential energy, that is, there is potential energy between it and the earth, to which the force of gravity tends to pull it. When it finally is pulled from its position it acquires kinetic energy as it falls, which it expends when it strikes the earth with a sudden force.

The force required to overcome the inertia of a body, as when first setting it in motion, is proportional to its mass. Hence weight = force = mass × acceleration; acceleration = gain in velocity ÷ time, and velocity = length ÷ time. It follows that all physical quantities are made up of length, mass, and time. The mass of a body increases with its velocity, mass being considered a relative quantity dependent upon the relative quantities length and time.

Matter exists in the solid, the liquid, and the gaseous states. Solids may be melted, and then boiled, to form gases, although some of the elementary solids, as carbon and tungsten, simultaneously melt and boil at relatively high temperatures, that is, they change directly from the solid to the gaseous state. That is why they have been used as filaments for incandescent lamps. Since heat is a form of energy, each individual part of a gas or a vapor contains more energy than any individual part of the same substance in the liquid or solid state. The difference between a gas and a vapor is that the latter is in contact with a liquid from which it is derived.

A mixture of matter may be mechanically sorted until such sorting is no further possible. Then the chemist comes in to do some further sorting. The smallest part of matter formerly was supposed to be the atom. There are 93 kinds of atoms and all have been discovered. Atoms combine to form chemical compounds, the smallest part of which is a molecule which may consist of a very few or very many atoms in chemical combination. There are substantially ten thousand known chemical compounds, about two-thirds of which contain carbon, all made up from only 93 kinds of atoms, many of which enter but sparingly into these compounds.

Up to the present century the atom was supposed to be solid. Then came the discovery of the electron (or negatron) and that the atom not only is nearly empty because of the relatively great distances between its parts, but the electron and the atom now

are known to have wave lengths which have been measured. This led General Smuts to remark:

> Matter itself, the time-honored mother of all, practically disappeared into electrical energy.
>
> "The cloud capp'd towers, the gorgeous palaces,
> The solemn temples, the great globe itself;"
>
> yea, all the material forms of earth and sky and sea were dissolved and spirited away into the blue of energy.

2. The electron is the carrier of the smallest negative electrical charge ever discovered, a negative charge being that obtained on hard rubber when rubbed with catskin. Furthermore, all negative electrons forced out of different kinds of atoms, possess exactly the same minute charge and otherwise are identical. In fact, all kinds of matter are found to be made up of electrons and protons, the proton being positively charged. The magnitude (Fig. 1) of the charge of the proton, however, is equal to that of the electron.

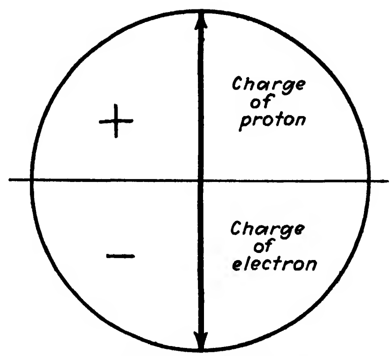


Fig. 1.—Illustrating the fact that while the charges of the proton and of the electron are of opposite sign the charges are numerically equal, as indicated by the arrows which point in opposite directions but have equal lengths.

All negative charges mutually repel each other and all positive charges mutually repel each other, but negative and positive charges mutually attract each other (Fig. 2), the forces of attraction and repulsion varying directly as the product of the two charges, and inversely as the square of the distance between their centers (Fig. 3). Hence the force of repulsion between two electrons would be the same as the force of repulsion between two protons under similar conditions. Protons are hydrogen atoms minus one electron, or the nuclei of the hydrogen atoms, while free electrons continually are being set to work in quantities that stagger the imagination. Since the earth is negatively charged because of its being constantly bombarded with electrons from the sun, there are enormous numbers of electrons lying around loose, so to speak.

In the study of electronics one deals with seemingly inconceivable large and small numbers. For example, when a current of 1 ampere is flowing in a wire, 6.281 billion billion electrons

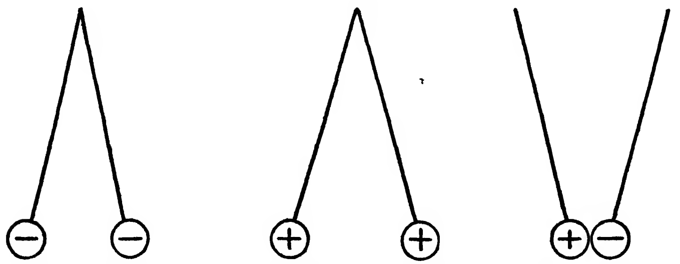


Fig. 2.—Showing repulsion ot like kinds of electricity and attraction of unlike kinds

pass a given mark on the conductor *every second,* and a billion is a thousand millions (in England a million millions)!

Electric energy is a commodity and electricity is its carrier. In the early days of the electric generating station when electric energy was consumed only in heating the filaments of incandescent lamps and the connecting wires, the energy was delivered at a constant pressure or voltage and was sold at so much a *coulomb,* much as the energy contained in gasoline is sold at so much a gallon, the coulomb being the common or practical unit quantity of electricity. There are 6.281 billion billion electrons in a negative coulomb and the charge of the electron is 0.1592 billionths of a billionth of a coulomb. Another name for the coulomb is the *ampere-second,* meaning that when a current having a strength of 1 ampere flows for 1 second, 1 coulomb flows past a given mark on the conductor.

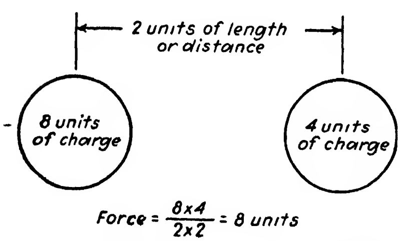


Fig. 3.—Illustrating the force between two charges.

In a conductor containing 1 coulomb of free electricity per inch of its length the current strength is 1 ampere when the constant average velocity or speed of the electricity is 1 inch a second (Fig. 4). For this reason the flow of electricity in a metal conductor or wire has been compared to the flow of water in a pipe, although it will be understood further on that this comparison is extremely crude.

The electron is the lightest known part of matter. It is 1,846 times lighter than the lightest of all the 93 kinds of atoms—the hydrogen atom. One gram is 2.2 thousandths of a pound. The mass of the electron at ordinary velocities or speeds is 0.8999 billionths of a billionth of a billionth of a gram! It is because of the exceedingly small mass of the electron that it can be given such tremendous speeds in exceedingly small time intervals in free space, a speed of 167,000 miles a second having been observed in a vacuum tube. The speed of light is 186,411 miles a second. Nothing can travel faster than light.

The mass of the electron increases with its speed. If it ever could travel at the speed of light, its mass would be infinite. The so-called "beta particles" shot out by radioactive substances, like radium, are electrons traveling at speeds not much below the speed of light. Experiment shows that the mass of one of these

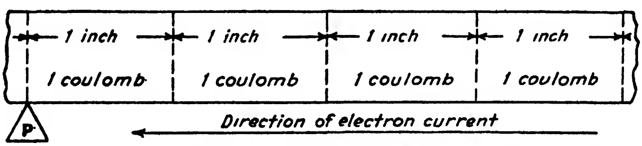


FIG. 4.—When 1 coulomb of electrons passes the pointer *P* uniformly every second the current strength is 1 ampere and its speed is 1 inch per second. If the speed is 2 inches per second, the current strength is 2 amperes, and so on.

high-speed electrons is much greater than the mass of an electron at ordinary velocities. Since matter consists of swarms of electrical charges, it is believed that all mass is electromagnetic in character. While we appear to be at rest, actually the earth moves at the speed 19 miles a second around the sun and the sun also travels at high speed through space, so the earth describes helices in space. The speed of a spiral nebula far away in space has been measured as 1,000 miles a second[1] relative to the earth. If the nebula is at rest we are moving 1,000 miles a second. There is no way of finding which is moving if the other is at rest. All motions are relative.

An excellent example of relative motion in connection with electrons or with positive charges is shown in the experiment, originally made by Rowland, wherein bodies mounted on a wheel and charged with electrons produce sufficient magnetism to affect a compass needle when moved at great speeds, whereas the compass needle would not be affected at all when mounted

[1] Speeds of 12,500 miles a second are not unusual.

on the wheel beside the charged body and rotated with it, any more than if both the charged body and compass needle were at rest on a table. But nothing like matter is at rest in the universe. A charged body and a compass needle placed side by side on a table are traveling with the earth at high speed through space. Magnetism makes its appearance to affect the compass needle only when the *relative* speeds of the electric charge and the compass needle are different. Even then there is no sign of any magnetism to one traveling with the electric charge, only an observer at rest with respect to the compass needle would detect any magnetism. It is evident that magnetism is associated with every electric charge all of the time, only an observer must move with a compass needle at a different speed from that of the charge in order to detect it. All charges produce magnetism by their motions.

The fact that the electron possesses mass makes electron currents or electric currents tend to resist being set in motion, to remain in motion when once set in motion, and to tend to resist being stopped, by virtue of their inertia, a quality common to currents of matter as those of water.

The electron not only possesses a peculiar combination of electrical charge and mass, but it also shows a singular combination of rotation and wave motion, the wave appearing to be associated with the electron and directing its motion. Experiment also has proved that an electron is a tiny magnet which may be turned one way or another in a magnetic field. The electron appears to spin and, since it has a charge, this may account for its being a tiny magnet.

The electrons obtained in certain forms of vacuum tubes are obtained from the filament by heating it with an electric current until its temperature becomes so great that the electrons are boiled right out of it. This indicates that there are free electrons in metal conductors. In solid metals the atoms are so closely packed together that the adjacent atoms mutually share some of each other's electrons, so to speak. Consequently, these electrons wander somewhat at random throughout the metal as an electron gas, each electron moving in a somewhat haphazard manner with no two electrons doing the same thing at the same time, and colliding with atoms in their movements.

Under the action of an electric driving pressure or voltage there is an average drift of these free electrons in the direction

of the voltage, this drift being the electric current. In vacuum tubes, however, the electrons travel faster and faster away from the filament under the influence of the applied voltage, attaining great speeds by the time they collide with the atoms of the metal plate from which they may knock other (secondary) electrons, produce x-rays, and also heat the plate to brilliance when the driving voltage is sufficiently great. In this respect, an electron acts more like a tiny bullet shot from a high-powered rifle, often being shot clear through aluminum foil windows of tubes and into the outside air, or else striking another electron and causing that to dart onward in its place.

Electric conduction in liquids and gases is more complicated. For example, in a tube filled with the inert neon gas at low pressure electrons projected through the gas collide with the atoms thereof, thereby ejecting secondary electrons from them which momentarily leave the atoms positively charged. The electrons thus ejected then collide with other atoms under the influence of the driving voltage until a large proportion of the atoms momentarily become positively charged through losing electrons. An electrically charged atom or molecule is an *ion*, so the positively charged atoms are positive ions, and the gas is said to be ionized. But positive ions constantly are recombining with electrons and each combination is accompanied by a minute flash of light. Hence the glow of the glow lamp or glow tube. Similar effects take place in electric sparks, arcs and lightning. From the foregoing, it will be observed that the proton is a hydrogen ion.

Electrons are driven out of metals by heat, as in the lamp filament; by light striking the surface of a metal, as in photoelectric cells; by the impact of projected electrons; by chemical action; by strong electric fields, and by natural disintegration, as of radium, as hereinafter described. Light is produced by the motions of electrons in atoms.

Since electrons are parts of every form of matter it is obvious that there is no physical, chemical, mechanical, electrical, or other phenomenon that is not influenced in some manner by electrons. It is obvious, therefore, that the field of application of electronic devices has no end and, even though such devices and their applications increasingly are being used in various branches of communication, science and industry, the electronic art has only begun, for man is learning how to crack the nucleus of the atom.

3. Units and Numbers.—While numerical relations herein are avoided as much as practicable, sometimes it is necessary or desirable to change from one system to another system of units for simplicity, at least. For example, the centigrade-gram-second system of units has two certain branches, the electrostatic and the electromagnetic units, which are related through the velocity of light—30 (more exactly, 29.986) billion centimeters, or 186,411 miles, a second. It is more practicable to employ electrostatic units when dealing with electric charges in some instances, and to use electromagnetic units when dealing

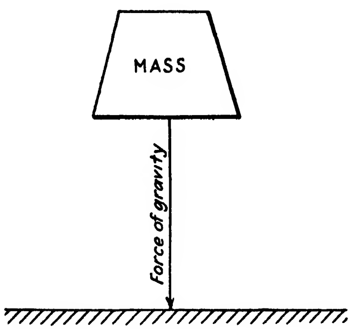


FIG. 5.

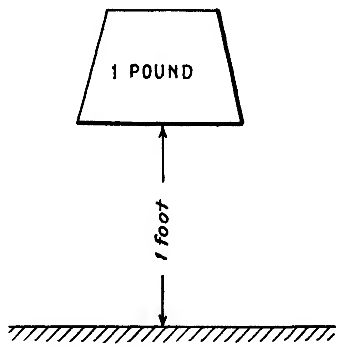


FIG. 6.

FIG. 5.—Mass and weight are not the same, although a mass of 1 gram has a weight of 1 gram. The mass of a body is constant while its weight varies with height above the earth and latitude. The weight of any mass is zero at the center of the earth. It has been proposed that the weight of 1 gram of mass be called 1 grammal. The terms "1 gram mass" and "1 gram weight" have different meanings, the latter being 981 times (the acceleration due to gravity in centimeters per second) greater than the former.

FIG. 6.—Illustrating the meaning of the foot-pound.

with electric currents. Then there are the so-called practical units, and so on, hence only a brief description of some of the units and their values in more familiar units will be given.

The gram is the mass (Fig. 5) of a cubic centimeter of water at 4 deg. C. The dyne is the force required to speed up or accelerate 1 gram of matter from dead rest to the speed 1 centimeter a second in exactly 1 second, and is equal to 2.248 millionths of a pound. The foot-pound is the work done in lifting 1 pound of matter vertically through the distance 1 foot (Fig. 6). The erg, or dyne-centimeter, is equal to 73.76 billionths of a foot-pound. The statcoulomb is the electrostatic unit of electric quantity, as of electrons. There are 2.095 billion electrons in a statcoulomb

TABLE I.—ABBREVIATIONS FOR AND VALUES OF SOME PHYSICAL QUANTITIES

Abbreviation	Quantity	Value
Å	Ångström unit (wave length)	1 ten-billionth (10^{-10}) m 1 ten-millionth (10^{-7}) mm = 0.1 mμ
a. c.	Alternating current	
amp.	Ampere	Coulomb per second
c	Cycle	
C	Centigrade	
cgs	Centimeter-gram-second	
cmb	Coulomb	Ampere-second
cm	Centimeter	0.01 m = 0.3937 in.
cu.	Cubic	1 cu. cm = 0.061023 cu. in. 1 cu. in. = 16.387 cu. cm
d. c.	Direct current	
deg	Thermometric or angular degree	
F	Fahrenheit	
ft.	Foot	0.304081 m
g	Gram	981 dynes 0.03527 oz.
hr	Hour	
in.	Inch	2.540 cm
k	Kilo	One thousand
kc	Kilocycle	1,000 c
kg	Kilogram	1,000 g 2.2046 lb.
kv	Kilovolt	1,000 v
kw	Kilowatt	1,000 w 1.341 horse power
lb.	Pound	16 oz. 0.4536 kg
m	Meter	100 cm 3.28083 ft.
ma.	Milliampere	0.001 amp.
mega	Million	
mi.	Mile	5,280 ft.
micro	Millionth part	
milli	Thousandth part	
min.	Minute	
mm	Millimeter	0.001 m 0.1 cm
mμ	Millimicron	One-millionth millimeter 10 Å
sec.	Second	
sq.	Square	1 sq. cm = 0.1550 sq. in. 1 sq. in. = 6.45163 sq. cm
v	Volt	0.003333 statvolt
w	Watt	0.001 kw
μ	Micron	Millionth part
μa	Microampere	One-millionth ampere
ω	Ohm	

of electrons. When 1 statcoulomb of electrons is placed 1 centimeter away from another statcoulomb of electrons, center to center, in air they mutually repel each other with a force of 1 dyne. The coulomb is three billion times greater than the statcoulomb. The statvolt is the electrostatic unit of electric potential or voltage and is equal to 300 volts.

One million = 1,000,000 = 10^6; 1 billion = 1,000,000,000 = 10^9; 1 trillion = 1,000,000,000,000 = 10^{12}; 1 millionth = 0.000 001 = 10^{-6}; 1 billionth = 0.000 000 001 = 10^{-9}; 1 trillionth = = 0.000 000 000 001 = 10^{-12}, and so forth.

Further relations are given in the table of abbreviations on page 9 used in this volume.

CHAPTER II

POTENTIAL ENERGY, POTENTIAL, AND CAPACITY

Since electric potential or voltage always is associated with electric charges that mutually repel or attract each other, thereby producing forces that tend to move the electricity, it is important that electric potential be understood at the outset. When potential energy in connection with electric charges thoroughly is understood, the meaning of electric potential—or simply potential—becomes clear since it merely is the potential energy stored or expended per quantity of electricity moved in storing or expending it. The capacity of a charged body is simply the ratio of the charge to the potential due to the charge. Capacity is the same as capacitance, a term which will be used in connection with electric condensers.

4. Potential Energy.—This and kinetic energy are the only two fundamental forms of energy thus far discovered, the latter being that expended in setting a body in motion and which then travels with the body. Potential energy is that form which is available for future use, as in the case of a suspended weight which can do work in falling. Potential energy also may be stored by forcing things together that constantly tend to force each other apart. Thus potential energy may be stored by compressing air or other gas, as in a tank. The more potential energy there is stored in such a tank of constant dimensions the greater become the pressure and the force. If energy is drawn off, however, there is a fall in the supply of potential energy and in the pressure and the force. In such a case, pressure is the energy per unit volume or the force per unit surface or cross section.

Since electrons mutually repel each other, potential energy may be stored between electrons by forcing them upon the surface of a body, preferably a metal sphere, where they cling but tend to push each other off when the force of mutual repulsion between them becomes too great. Regardless of where the electrons are placed upon the metal sphere they mutually repel each other

sidewise, across the diameter and in every conceivable direction through the sphere, so that they tend to be equally spaced all over the surface of the metal sphere, as shown in Fig. 7. Hence the sphere may be either solid or hollow.

Let us take a metal sphere a little more than ¾ in. in diameter, that is, let its radius be 1 cm, and figure how much potential energy we could store on the surface of that sphere if we had the means at our command to supercharge it, so to speak, providing that it could be done, recalling that we can figure out many things that, for various practical reasons, we cannot actually accomplish. Let us make a bold attempt and see how much potential energy we could store by placing 1 g of electrons on the sphere's

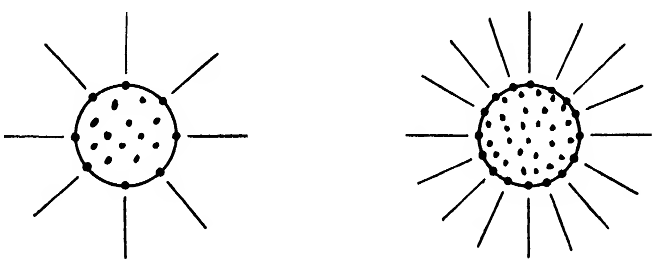


FIG. 7.—Illustrating the uniform distribution of electrons on the surface of a negatively charged metal sphere. The greater the number of electrons there are on a given sphere the greater are said to be the surface density of charge and the potential.

surface. One gram weighs only 2.2 thousandths of a pound, but 1 g of electrons contains 177 million coulombs. Our figures show that if we had a machine of 1 trillion-kw output for placing electrons on that sphere and keeping them there, we would be able to get all of the 177 millions of coulombs of electrons on its surface after running the machine continuously for about half a million years!

The force of mutual attraction due to gravity between 2 g of electrically neutral (uncharged) matter placed 1 cm apart, is only 14.6 billionths of a billionth of a pound; we wonder what the force of mutual repulsion between 2 g of electrons would be. We find that if one gram of electrons were placed at the north pole and another gram of electrons at the south pole of the earth, they would be close enough to repel each other with a force of 191 million tons.

That is altogether too much for our purpose, so we shall be more conservative and figure on charging two very small similar

spheres with only 1 cmb of electrons each. We reason that the short-circuit current of a flashlight dry cell is only about 2 amp., or 2 cmb per second, and since the flashlight dry cell is a harmless thing a charge of 1 cmb of electrons on each of the small spheres would seem reasonable. But once more we have assumed too much, for our figures show that if they were placed 1 cm apart in air they would mutually repel each other with a force of 20.2 trillion pounds or 10.1 billion tons, and even when placed a mile apart they still would repel each other with a force of 780 lb.

If 2 cmb of electrons slowly pass a given mark within a small wire every second when the current strength therein is 2 amp., and 2 cmb of electrons placed 1 cm apart in air repel each other with a force of 10.1 billion tons, it looks as though there must be a large amount of energy stored up in a very small amount of matter.

Nature makes the mighty from the small. She has a superabundance but usually gives out only a little at a time from her storehouse, for too much at a time destroys. A slight difference in atmospheric pressure makes the gentle breeze—a great difference causes the hurricane. A small difference of potential causes a small useful electric discharge—a great one produces lightning.

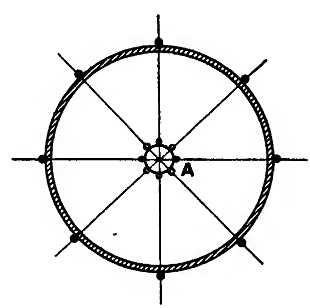


FIG. 8.—A uniformly distributed charge on the surface of a sphere acts as though it were concentrated at *A*, the center of the sphere.

Finding that we cannot figure practically in terms of grams and coulombs of electrons when it comes to placing electrical charges on the surfaces of small spheres, we shall place 1 statcoulomb of electrons on a metal sphere having a radius of 1 cm, a task easily accomplished. The electrons will mutually repel each other so that they will be uniformly distributed all over the surface of the sphere. They will then act outwardly as though they were all concentrated at the very center of the sphere (Fig. 8). Conversely, any charge of electricity, as 1 statcoulomb of electrons, packed into the smallest conceivable space acts outwardly in all directions as though the same electrons were uniformly distributed on the surface of a sphere of any radius whatever, provided it is not too great.

When a soap bubble is charged with electrons, the mutual repulsion between them causes the bubble to expand, thereby permitting the electrons to move farther away from each other. We shall consider a very small charge concentrated at a point and then assume that it expands like a soap bubble so that the electrons always, at any instant, will be equally spaced and at equal distances from the center. Figure 9 shows the spacing of the electrons at the "rim" of the sphere for two positions after expansion, as well as with the charge concentrated near the center. If we permit only one electron to move from the central group, it will travel in one of the infinite number of possible directions from charge A. Then work would be done and potential energy stored in returning the escaping electron to charge A.

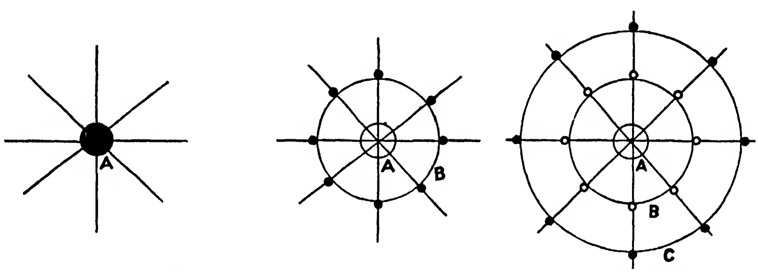


FIG. 9.—A charge at a point (here exaggerated) has exactly the same effect on a distant charge as an equal number of uniformly spaced small charges (as electrons) at any radial distance from the common center A.

We shall concentrate 1 statcoulomb of electrons at a fixed point and then move a similar statcoulomb of electrons toward it from any direction whatever. The force of mutual repulsion between the two charges varies inversely as the square of the distance, but the potential energy stored between them varies inversely as the distance between them. When they are 1 cm apart, the potential energy stored between them will be 1 erg. If work is done through their mutual repulsion until they are 2 cm apart, the potential energy will have fallen to 0.5 erg; if 4 cm apart, to 0.25 erg, and so on (Fig. 10).

Now let us move 100 statcoulombs of electrons toward 1 statcoulomb of electrons (Fig. 11). Then the potential energy stored will be increased a hundredfold at every point along its path, that is, it will be 100 ergs when they are 1 cm apart, 50 ergs at 2 cm, and so on.

Likewise if a charge of 100 statcoulombs of electrons were concentrated at a fixed point and 1 statcoulomb of electrons were

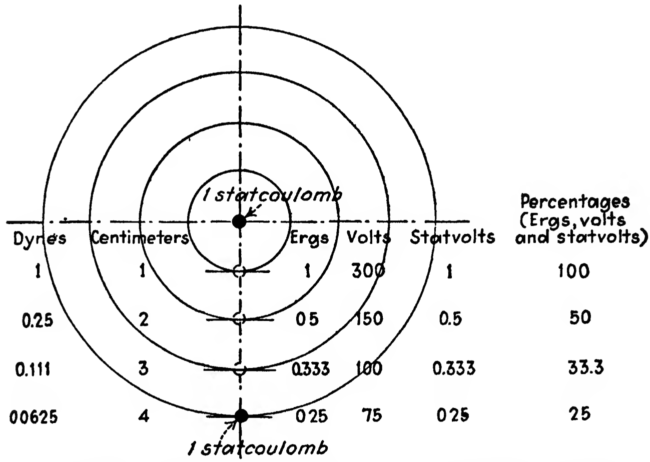


FIG. 10.—Conditions when the fixed charge is 1 statcoulomb and the movable charge is 1 statcoulomb.

moved toward it (Fig. 12), the potential energy would be 100 ergs at 1 cm, 50 ergs at 2 cm, and so forth, whereas if another

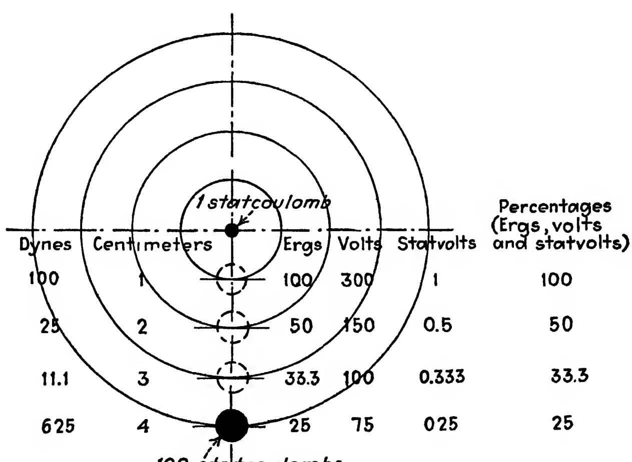


FIG. 11.—Conditions when the fixed charge is 1 statcoulomb and the movable charge is 100 statcoulombs.

charge of 100 statcoulombs of electrons (Fig. 13) were moved toward it, the potential energy would be 10,000 ergs at 1 cm,

5,000 ergs at 2 cm, and so on. But this would not in the least laffect the potential.

5. Potential is a shortened form for *potential function*—a mathematical term. Potential is a *ratio* and may be expressed as the potential energy per quantity of electricity moved. Hence, while the potential energy stored between 2 statcoulombs of electrons 1 cm apart is 1 erg (Fig. 10), and the potential energy stored

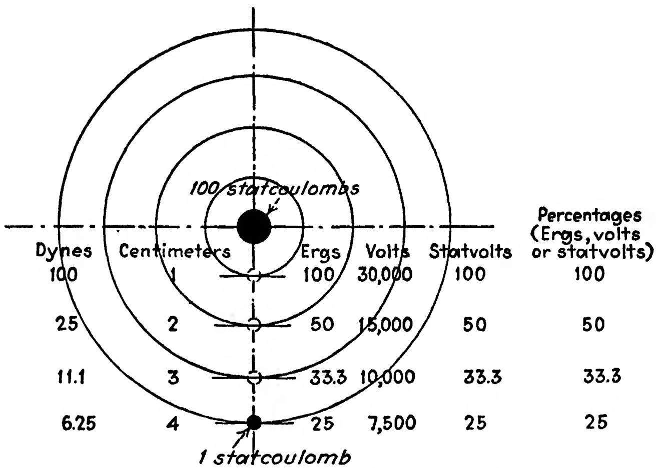


Fig. 12.—Conditions when the fixed charge is 100 statcoulombs and the movable charge is 1 statcoulomb.

between 100 statcoulombs of electrons and one statcoulomb of electrons 1 cm away is 100 ergs (Fig. 11), the potential due to the (fixed) charge of 1 statcoulomb of electrons in each case is the same—1 statvolt or 300 v. The potential of a fixed[1] charge is the ratio of (*a*) the potential energy stored in moving up a second charge toward it through a very great distance to (*b*) the magnitude of said second charge. A fall in potential refers to the energy expended (work done) per quantity of electricity moved, as when a charge moves under the influence of the mutual force of repulsion.

[1] A fixed charge is assumed for the purpose of reference. Obviously, the movable charge also has a potential. Thus the fixed charge in Fig. 11 is the movable charge in Fig. 12 and the movable charge in Fig. 11 is the fixed charge in Fig. 12. The *mutual potential* of two charges is the ratio of their product to the distance between them.

Hence we see that, while the potential energy varies directly as the product of the magnitudes of the fixed and movable charges and varies inversely as the distance between them, the potential varies directly as the magnitude of the fixed charge only, and inversely as the distance from said charge. It is independent of the magnitude of the movable charge, that is, while the potential is dependent upon the position of the movable charge it is not dependent upon its magnitude. That is why a charge on a sphere or other body is said to have a potential without reference to any

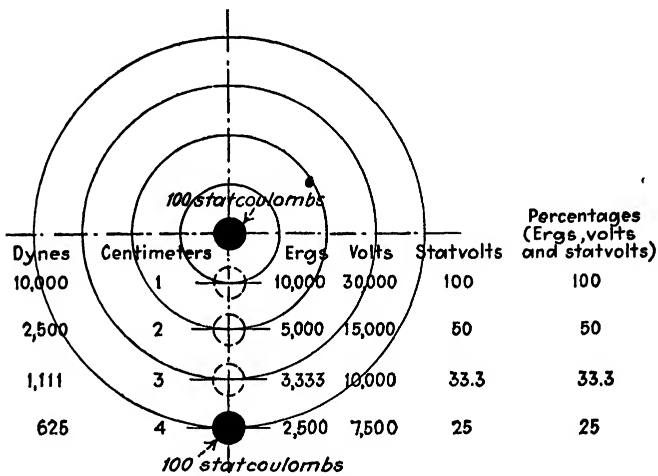


FIG. 13.—Conditions when the fixed charge is 100 statcoulombs and the movable charge is 100 statcoulombs.

other body or charge, but care always is taken to state that the potential falls off with distance as measured from the center of the charge.

Regardless of the magnitudes of the fixed and movable charges, the *percentage* of the potential energy and of potential, with the distance 1 cm as the position for 100 per cent, varies inversely as the distance from the fixed charge, and both fall off together at exactly the same rate (Figs. 10 to 13).

We also see that the potential of any sphere is the same at any point on its surface when its charge is uniformly distributed or is concentrated at its center, since another charge can approach it from any direction whatever. Hence the surface of a sphere, either real or imaginary, surrounding a central charge is called an equipotential surface.

From Fig. 10 we learn that the potential at the distance 1 cm from a concentrated charge of 1 statcoulomb is 1 statvolt. Hence the potential in statvolts of a sphere of 1-cm radius is numerically equal to the charge in statcoulombs. To charge a sphere of 2-cm radius to a potential of 1 statvolt (300 volts) requires that the sphere be charged with 2 statcoulombs; a sphere of 3-cm radius requires a charge of 3 statcoulombs, and so on. Hence if a sphere of 1-cm radius could be charged with 1 cmb (3 billion statcoulombs) of electrons, its potential would be 3 billion statvolts or 900 billion volts. The charge required to give a potential of 100,000 v or 333.3 statvolts to a sphere 10 in. (25.4 cm) in diameter is 4,230 statcoulombs or 1.41 millionths of a coulomb.

Potentials always accompany electric charges. While negative charges have been used for purposes of description, positive charges might have been employed.

No uncharged body can be given a potential, nor can the potential of a charged body be increased or diminished, without a movement of electricity of some kind, either of one or both of the charges, as when one is moved away from the other, or by the movement of electricity through a conductor from one charge to the other, under the influence of a force. Any movement of electricity is an electric current. Hence an electric current, however small, always flows when bodies are charged and discharged, as when potential energy is being electrically stored or expended. The magnitude of such a charge may be calculated from the strength of the charging current at every instant and the time during which the charging current flows.

6. Capacity.—The electrostatic capacity, or simply the capacity, often called capacitance, of a sphere is the ratio of the charge in statcoulombs to the potential in statvolts. Since the condition for unit potential is that the charge must be numerically equal to the radius in centimeters, it follows that the capacity of a sphere is proportional to its radius, that is, the capacity of a sphere of 1-cm radius is 1 statfarad; the capacity of a sphere of 2-cm radius is 2 statfarads, and so forth.

7. Difference of potential may mean a rise in potential as when potential energy is being stored between two charges, or a fall in potential as when work is being done through the expenditure of stored electric energy. For example, when 100 statcoulombs of electrons are 1 cm away from a fixed charge of 1 statcoulomb

of electrons, both being concentrated at fixed points (Fig. 11), the potential energy is 100 ergs and the potential of the fixed charge is 300 v. Now let some of this potential energy be expended in doing work while the distance between the two charges increases from 1 cm to 4 cm. Then the potential energy will have fallen from 100 ergs to 25 ergs, a difference, or fall, of 75 ergs, and the potential will have fallen from 300 v to 75 v, a difference of potential of 225 v.

The work done during a fall of potential always is equal to the product of the fall in potential and the quantity of electricity moved in causing the fall, and also is equal to the product of the average force and the distance the electricity is moved during the fall, when the unit of potential is the statvolt, the unit of electric quantity is the statcoulomb, the unit of force is the dyne, and the unit of length is the centimeter. That is the basis upon which the whole idea of voltage is founded. It is based upon mechanical force electrically produced. There is no difference between 1 dyne of force due to the pull of gravity and 1 dyne of force between two electric charges.

The average force during the known movement of a known quantity of electricity may be easily determined when the fall in potential also is known. In the above example in connection with Fig. 11 the work done in moving 100 statcoulombs of electrons through the distance 3 cm, accompanied by a fall in potential of 225 v or 0.75 statvolt, is equal to 0.75 statvolt $\times$ 100 statcoulombs = 75 ergs or dyne-cm.[1] Since the distance or length of movement of the electricity is 3 cm, the *average* force during the movement is equal to 75 ergs $\div$ 3 cm = 25 dynes.

It is easy enough to measure the fall in potential along a wire or filament when an electric current is flowing therein by means of a voltmeter, and it also is a simple matter to determine how many statcoulombs of electricity (as calculated from the measured number of coulombs) pass a given point on the wire every second by measuring the current strength with an ammeter (Fig. 14), and in that manner find how much energy is converted into heat every second between two points on the wire where we connect other wires to our voltmeter and between which the fall in potential is measured; however, since we do not know the

[1] The joule or watt-second is equal to 10 million ergs or dyne-cm. Fifty joules of electric energy are converted into light and heat in a 50-watt lamp every second.

distance through which the current of electricity moves during each second inside the wire, we can know nothing about the magnitude of the force that is driving the electricity. That is

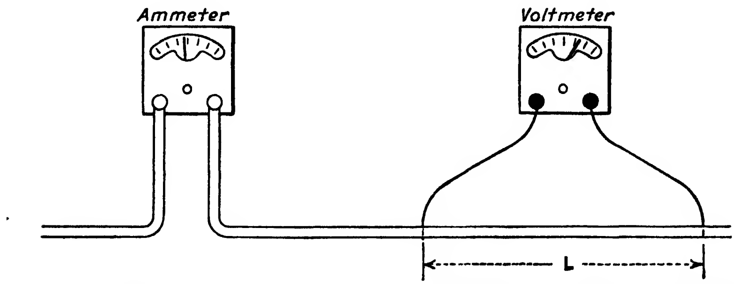


FIG. 14.—The expenditure of energy *per second* and the fall of potential are measured only over the length L of the wire. The greater the length L the greater is the expenditure of energy *per second* and the greater is the fall of potential. When the current strength is constant, the supply of potential energy is being renewed as rapidly as it is being expended.

where the great mystery lies. There is no mystery about the meaning of potential or voltage, even though the real reason why electric charges produce mechanical forces is unknown. Voltage

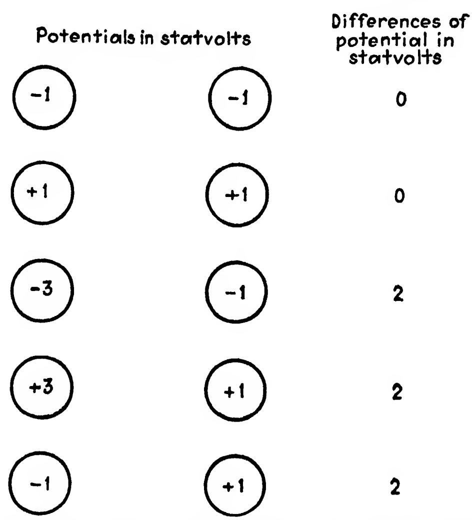


FIG. 15.—Showing how various differences of potential may be obtained by varying the magnitudes of the kinds (polarities) of charges.

is not to be confused with force. Because of its nature it behaves more like a pressure in electric conductors, the pressure per volt varying with the kind of conductor, since the real pressure

depends upon how much free electricity is contained within a given volume of conductor.

Difference of potential also refers to the difference between the potentials of two charges. Referring to Figs. 11 and 12, the potential 4 cm away from a charge of 1 statcoulomb of electrons is 75 v, while the potential 4 cm away from a charge of 100 statcoulombs of electrons is 7,500 v, and the difference of potential is equal to 7,500 − 75 = 7,425 v. If 1 statcoulomb of positive ions were substituted for the statcoulomb of electrons, the difference of potential would be equal to 7,500 + 75 = 7,575 v (Fig. 15).

If two spheres are charged to different potentials with electrons, the difference of potential between them is found by subtracting their potentials. The same statement holds for positive charges. But when one of the spheres is negatively charged and the other positively, the difference of potential is found by adding their potentials as in the above example. Hence by giving one body a negative charge and another body a positive charge the difference of potential may be double that of either body, whereas if like charges are placed on each body the difference of potential between them may be zero.

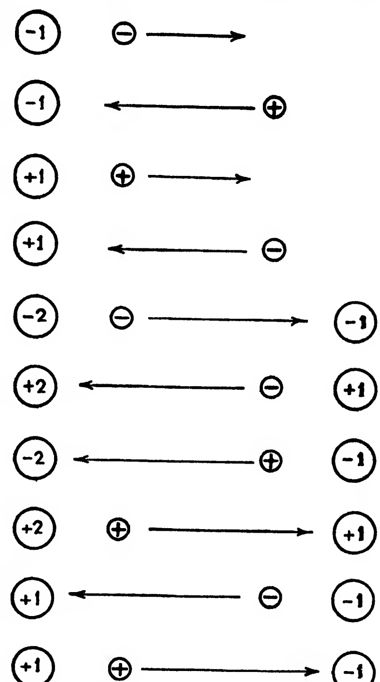


Fig. 16.—Showing how free charges move according to the polarities of the charges and the differences of potential. Distances are here disregarded.

The application of this principle is a powerful means of controlling electric currents since electricity always moves from points of high potential to points of lower potential, that is, electrons move away from *negative* charges toward charges of lower negative potential or toward positive charges, while positive ions move away from *positive* charges toward charges of lower positive potential or toward negative charges, as shown in Fig. 16.

Machines are driven by the mechanical force exerted by the pull of gravity on water; by the mechanical force of expanding gas and steam; by the mechanical forces produced by electric currents as in electric motors; and they also have been driven by the mechanical forces developed between electrically charged bodies, although the latter machines never have been very powerful because man even now is only learning how to keep within bounds the necessary electrical charges under the influences of the relatively great mechanical forces that must be exerted between them to make such electrical machinery practicable. Dr. K. T. Compton has been quoted as saying that he believes the day of electrostatic apparatus is approaching through man's increasing knowledge of electric insulation. Van de Graaff's electrostatic generator operating at a difference of potential of 10 million volts, and described in Art. 18, is an advance in that direction.

CHAPTER III

ELECTRONS AND IONS

Electricity is conducted in four general manners under the influence of an electrically produced force. It is shot through space or vacuum much as bullets are shot. In gases and vapors the atoms and molecules constantly are moving about at high speeds and continually collide with each other. When bombarded with electrons—some of which may be uncombined with atoms in the gas since there is a vast surplus of electrons at and near the earth's surface—the gas becomes ionized as described in Art. 2, resulting in electrons moving rapidly in one direction to form a negative current and positive ions drifting more slowly in the opposite direction to form a positive current. Electric conduction in liquid chemical compounds consists of exceedingly slow movements of negative and positive ions in opposite directions after molecules are taken apart, that is, dissociated. Electric conduction in solids has been outlined in Art. 2. The electron was predicted and its charge quite accurately estimated through a knowledge of gases and electric conduction in liquids long before it actually was isolated through the medium of the vacuum tube. This chapter includes a brief story of how it came about.

8. The Nature of a Gas.—In 1811, Avogadro stated his law that equal numbers of molecules of all the more perfect gases are contained in equal volumes at equal temperatures and pressures. This law also applies to the atoms of elementary substances. Scientists of the time supposed that the molecules of gases were like bubbles and were packed closely against one another. When the temperature was increased the bubbles tended to expand and thus formed a pressure on the walls of the containing vessel.

Waterston showed in 1845 that the molecules were very much smaller than supposed and that they were moving about at high speeds, colliding with one another and with the walls of the containing vessel and, therefore, exerting a pressure due to their motions or, rather, to their kinetic energy. Kinetic energy is

that carried by a body in motion. It is equal to half the product of the mass and the square of the velocity of a body. Pressure may be defined as the energy per unit volume. The greater the temperature of the gas the greater became the speeds of the molecules, so the pressure was proportional to the mean speed. Waterston's statement was not believed at the time, but a few years later Clausius restated the principle, and with the help of Maxwell and others the kinetic theory of gases was developed.

Clausius determined the mean speed of the molecules in 1860, and Maxwell determined the mean length of path of flight between collisions. These determinations immediately were followed by Stoney's estimates of the number of molecules present. This proved to be about 40 billion billion molecules per cubic centimeter in a gas, or mixture of gases, at standard temperature and pressure.

Compton has stated that a little thimble filled with helium gas at atmospheric pressure would contain about 10 billion billion atoms. So widely are gaseous atoms and molecules distributed in the course of time, and so many are there in a small space at any one time, that it is probable that some of the molecules from Caesar's last gasp are in every room in every house.

9. A Bit of Chemistry.—The mass of the hydrogen atom now is known to be 1.663 trillionths of a trillionth of a gram. Since the relative masses of the different kinds of atoms are directly proportional to their atomic or relative combining weights, it is a simple matter to determine the mass of any kind of atom by comparison with the known mass of the hydrogen atom. Thus the mass of the chlorine atom is 58.516 trillionths of a trillionth of a gram.

We know that one atom of hydrogen (H) combines with one atom of chlorine (Cl) to form one molecule of hydrochloric (muriatic) acid (HCl); they combine in the proportion of Cl to H $= 58.516 \div 1.663 = 35.187$ g of Cl to 1 g of H. While these are the relative combining weights or masses of H and Cl in any system of weights, as in grams, pounds, tons, and so forth, the relative combining weight of oxygen is taken as 16.0000 as a standard by which all other relative combining weights are reckoned. This adjustment changes the relative combining, or atomic, weight of H to 1.0077 and that of Cl to 35.458. Thus 1.0077 g (or 1 gram atom) of H combines with 35.458 g (1 gram atom) of Cl to form $1.0077 + 35.458 = 36.4657$ g (1 gram

molecule) of HCl. If an attempt is made to combine H and Cl in any other proportion there will be some of one or the other left over that had nothing to combine with.

H–Cl H–O–H

A. Hydrochloric acid. *B*. Water.

FIG. 17.—Graphical representations of molecules. The dashes between the chemical symbols are the "bonds" of the chemist.

Atoms combine with other atoms to form molecules singly and in groups of 2, 3, and so forth. Thus 1 atom of oxygen (O) combines with 2 atoms of hydrogen (H) to form 1 molecule of water (H_2O). The ratios 1, 2, 3, and so forth, are the valencies of the atoms which may change for a given kind of atom, dependent upon how much stronger it is than the kind of atom with which it combines.

While the formula H_2O means that there are two H atoms and one O atom in the water molecule, the valence of the oxygen atom is 2 and that of hydrogen is 1 in that molecule. An oxygen atom may be thought of as being able to overpower and capture 2 hydrogen atoms or, conversely, 2 hydrogen atoms are required to capture one oxygen atom to form one H_2O molecule.

The meaning of valence is indicated in Fig. 17. The "bonds" of the chemist now are called valence electrons, for reasons which soon will be made clear.

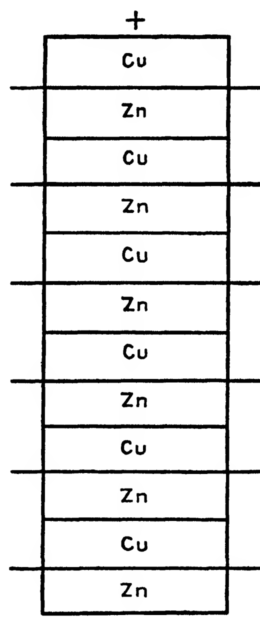


FIG. 18.—Volta's pile. Cu = copper. Zn = zinc.

10. Electric Cells.—The electrification of bodies by rubbing was known to the ancients. Volta proved that two different kinds of metals respectively became negatively and positively charged when placed in contact with each other in air. Although the charges were quite feeble, he showed that they could be made as strong as desired by using a number of pairs of disks of these metals placed in contact with each other, and then separating the pairs from each other with brine-moistened paper or cloth (Fig. 18) to form a "pile." In this manner he added up the

potentials of the charges of the different kinds of metal. The unit of potential was named the volt in honor of Volta.

Volta made the forerunner of the modern electric battery by placing copper and zinc strips in acidulated water and properly connecting them in series, that is, a copper strip to a zinc strip, as he did in his pile, and so on for all of the other cells (Fig. 19). The principle was exactly that of his pile. The electric current due to this "crown of cups" (they were placed in a circle) flowed in the wires in one constant direction in a closed circuit and was strong enough to ring a modern electric bell and also could heat a small wire. The greater the number of cells or "cups" the greater became the total difference of potential or voltage.

In such a general type of primary cell the difference of potential never exceeds 2 v. The liquid may consist of water containing, say, about 10 per cent of sulphuric acid. The current flows because a difference of potential is maintained by the sulphuric

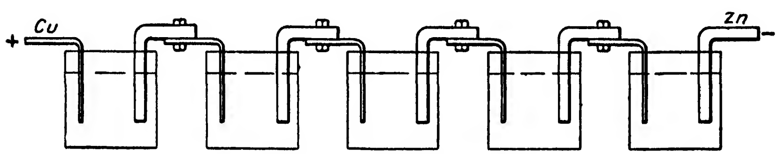


Fig. 19.—Volta's battery.

acid dissolving the zinc through chemical action which releases large numbers of valence electrons that are literally forced upon the remaining zinc, thereby producing and maintaining its negative charge. But electrons must move inward from the copper to keep the current circulating. About how this takes place may be gathered from the reverse process described below.

11. The Electron Foretold.—Various articles are electroplated by placing them in a solution of the salts of the metal to be deposited on the surface of the baser metal or alloy, as when electroplating brass articles with silver, and then causing an electric current to flow in the solution in such a direction through the external circuit that the precious metal shall be dissociated from whatever it was combined with and be deposited, atom by atom, upon the baser metal or alloy. Such a cell is termed an electrolytic cell, and the solution is the electrolyte or solute.

Faraday, in 1833, made the discovery that whenever univalent (valence = 1) elementary substances are deposited or released in the electrolytic cell, the quantities of electricity (as ampere-

seconds) required were proportional to the ratio of (*a*) the weights of the elementary substances deposited or released to (*b*) the atomic weights of said substances, 96,500 coulombs (amperes × seconds) being required for the electrolysis or release and transfer of 1 gram atom (1.0077 g) of hydrogen, 1 gram atom (35.458 g) of chlorine, and so forth.

What this really means is that the passage of 96,500 coulombs (as 10 amp. for 9,650 sec.) decomposes 36.4657 g (1 gram molecule) of HCl into the above constituents of H and Cl. Faraday also determined the laws for other valencies. Thus in the electrolysis of H_2O a given number of coulombs would transfer and release twice as many H atoms as it would O atoms.

In 1874, Stoney, who previously had estimated the number of molecules present in a given volume of gas, divided the quantity of electricity required for the electrolysis of a cubic centimeter of hydrogen by the number of atoms present; he found the quantity of electricity per atom to be 0.01 billionth of a billionth of an abcoulomb (10 cmb). This quantity of electricity per monovalent atom he called an "atom of electricity" and, in 1891, gave it the name *electron.* The present known charge of the electron as determined by an entirely different method than the foregoing is 0.01592 billionth of a billionth of an abcoulomb, and Stoney, therefore, made a very close estimate.

Thus the work of Clausius, Maxwell, and Stoney, starting with the molecules in a gas, combined with that of Faraday and Stoney in connection with liquids, predicted the electron and its charge before it ever was absolutely isolated and before its charge was accurately measured by Millikan.

We now know with great certainty the number of atoms in a cubic centimeter of a gas, liquid, or solid. Each gram atom, or combining weight in grams, contains 0.6061 trillion trillion atoms. This number is termed Avogadro's number—the number of atoms in 1.0077 g of hydrogen, 35.458 g of chlorine, and so forth. The number 96,500 is called the faraday in honor of the great physicist.

12. Ions.—Pure water is a very poor electric conductor. However, when a small percentage of hydrochloric acid (HCl), for example, is dropped into it the resulting solution becomes conducting in proportion to the concentration or percentage of acid in it, because water possesses the remarkable property of splitting the HCl molecules into H and Cl ions, the H ion being

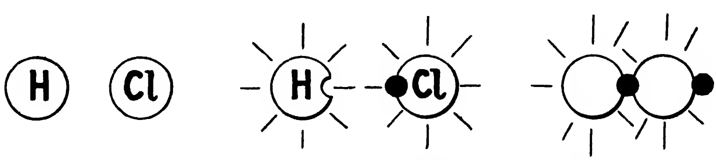
positively and the Cl ion negatively charged. The chemical action which takes place when the acid is put in the water does not affect the principle, as only the dissociated H and Cl ions take part in electric conduction.

A negative ion is an atom or molecule to which are added or attached one or more electrons which give it a negative charge. A positive ion is a previously electrically neutral atom from which one or more of its valence electrons have been removed. An H

A. Hydrochloric acid. *B*. Water.

FIG. 20.—Graphical representations of molecules, as herein employed. The black dots are the valence electrons holding the atoms together. The circles representing the atoms have no reference to their relative sizes or weights.

atom and a Cl atom become chemically combined to form an HCl molecule, due to the attempt of the Cl atom to rob the H atom of its single valence electron, but to which the proton—which is all that is left of a hydrogen atom after its valence electron is removed—refuses to release. Hence a chemical combination may be considered as a tug of war between atoms—between the H proton and the Cl atom in this particular case. When water splits the HCl molecule into one H ion (a single proton) and one Cl ion, it aids the Cl atom in robbing the H



A. Atoms. *B*. Positive ion. *C*. Negative ion. *D*. Negative ion.

FIG. 21.—Graphical representations of atoms and ions, H, Cl, and a molecule that has become negatively charged, in this case.

atom of its single valence electron, Cl taking the electron along with it, thus leaving the proton positively excited (see Figs. 20 and 21). Hydrogen is the only element (outside the neutron) in which only a proton remains when a single valence electron is removed from it.

A glass or other suitable vessel containing the HCl solution, into opposite ends of which are dipped platinum wires (or electrodes), forms a simple electrolytic cell (Fig. 22). When this

cell is electrically connected to a battery or a dynamo, the negative electrode of the cell repels the negative (Cl) ions and attracts the positive (H) ions, while the positive electrode repels the H ions and attracts the Cl ions. The result is a procession of the Cl ions through the solution away from the negative electrode and toward the positive electrode and another procession of the H ions, in the opposite direction, through the solution away from the positive electrode and toward the negative electrode. This results in an accumulation of H ions at the negative electrode because they move faster than the Cl ions; therefore, what follows is assumed to take place before the accumulation of ions occurs.

Thus there are two electric currents, a positive and a negative, traveling in opposite directions in the electrolytic cell. The currents are as separate and distinct, though necessary to each other, as though they flowed in separate channels. The magnetic and other effects of a current consisting of negative charges flowing in a given direction are identical with those due to a current of positive charges flowing in the opposite direction; the sum of the two current strengths, therefore, is the total current strength, which is the same as that flowing in the wires connecting the electrolytic cell with the battery.

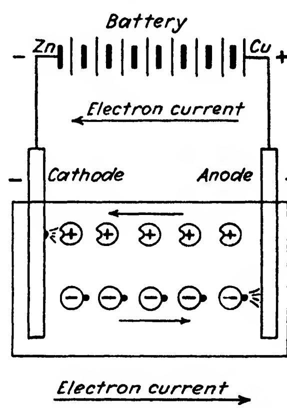


Fig. 22.—Principle of simple electrolysis.

When a Cl ion arrives at the positive electrode, it delivers its extra electron thereto and becomes a plain electrically neutral Cl atom. When an H ion arrives at the negative electrode, it receives an electron therefrom and becomes an electrically neutral H atom. Hence every time a Cl ion delivers an electron to the positive electrode a similar electron is delivered to an H ion from the negative electrode, the passing of electrons to one end of the connecting wire and battery and out at the other end maintaining an electron flow in the connecting wires and battery as well as in the electrolytic cell, the action in the battery being of the general order of that in the electrolytic cell.

Thus it is seen that while there are free electrons in the metal electrodes and in the connecting wires, the electric current in the connecting wires is merely incidental to the removal of electrons

from the Cl ions and their delivery to the H ions under compulsion of the voltage from the battery. The Cl ions each have an extra electron and the H ions each need an electron to make them electrically neutral atoms. The Cl ions have to move through the electrolyte in order to deliver their extra electrons and thus make electrons available for neutralizing the H ions at the negative electrode. Hence electrons are pulled from the Cl ions and into one end of the connecting wires, and are pulled out at the opposite ends of the wires where they are seized by the H ions.

The positive electrode is the *anode* and the negative electrode is the *cathode.* But negative ions are anions and positive ions are cations, being named for the electrode toward which they move.

It is to be noted that the conventional or positive direction of current flow in a wire is the reverse of the direction of electron flow therein. This is due to the fact that nobody knew the real direction of the current in a wire when the direction was assumed. The copper electrode of a battery cell was named *positive,* the zinc electrode was named *negative,* and the direction of the current in the outside connecting wire was *assumed* to be from positive to negative. That is why that conventional current is called a positive current *in a metal conductor.* There are both positive and negative currents *inside* cells. This is just another example of chance. If one does not know, but has two guesses, the guess is just as apt to be wrong as right. The scientists who guessed that the current flowed *from* the positive electrode into a connecting wire just happened to make the wrong guess. Now we have to explain it for them to make clear the meaning of the conventional positive current which apparently does not exist in metal conductors. Yet they had to make an assumption.

As positive ions are repelled away from the anode and negative ions are repelled away from the cathode of an electrolytic cell the solution becomes diluted in those regions. By observing the time rates of dilution of various solutions near the respective electrodes in electrolytic cells, the speeds of various ions at stated temperatures have been determined by various investigators, notably Hittorff, Kohlrausch and Arrhenius. The ions of electrolysis move very slowly because they appear to drag a number of water molecules along with them through the solution.

An electric field strength of 1 v per cm is a unit electric field of force (attracting or repelling a charge) wherein the potential

varies by 1 v for every centimeter traveled in the direction of the force, that is, the voltage gradient or fall in potential per centimeter is 1 v per cm. Under these conditions the speed of the H ions, fastest of all the ions, is 0.00315 cm per sec., while that of the Cl ions is 0.000654 cm per sec. The ionic speeds at unit voltage gradient are termed their mobilities, which always are the same for each kind of ion at the same temperature regardless of the nature of the dilute solution.

13. A Study of Electric Conduction.—The fact that there are 0.6061 trillion trillion atoms in 1.0077 g of H, in 35.458 g of Cl, and so on, makes it possible for us to place as many H and Cl ions as we please in a given amount of water, up to a certain limit. If we have 1 cu. cm of pure water and 1 ÷ 96,500 = 0.0001036 gram molecule of HCl, we know that the HCl will be split up into 6.281 billion billion H ions and 6.281 billion billion Cl ions, that is, there will be 1 cmb of H ions and 1 cmb of Cl ions in the cubic centimeter of solution. Then we can deal with each kind of ion separately and thus be able to figure out the actual force driving the ions, because we know that when the fall of potential is 1 v per cm the speed of the H ions is 0.00315 cm per sec. and the speed of the Cl ions is 0.000654 cm per sec.

Considering only the Cl ions, let us make the cross section of our liquid conductor 1 sq. cm. Then it will contain 1 cmb of Cl ions per centimeter length, and a fall in potential of 1 v per cm will cause the ions to move at the speed 0.000654 cm per sec., thus making the current strength only 0.000654 amp. or 0.654 milliamp. (see Fig. 4). If we want a current strength of 1 amp., we must drive the ions 1 ÷ 0.000654 = 1,529 times faster, and this means that the fall in potential per centimeter also must be increased 1,529 times, that is, to 1,529 v per cm.

Since the force varies with the potential, the force required to drive just the single coulomb of Cl ions at the speed 1 cm per sec. may be determined. It is 15.59 million grams, 34,380 lb., or 17.19 tons. This force is 3 billion times greater than that required to move 1 statcoulomb of Cl ions through the liquid under identical conditions. The force varies directly as the quantity of electricity moved and the speed at which it is moved. This is because the more ions there are the greater is the total "drag," and the greater the speed the greater also the force required to maintain it.

The foregoing is worked out in exactly the same manner as the example in Art. 7, only volt-coulombs (joules) per second had to be reduced to gram-centimeters per second in the process. If we had a fleet of sailboats, we should expect them to go faster in a strong wind than in a mild breeze, and the more boats we had equally spaced in a mile stretch the greater would be the number that would cross a given line in a given time.

Voltage acts like a pressure because it is independent of the magnitude of the quantity of electricity moved. Thus we can double or treble the cross section of our liquid conductor, that is, put two or three coulombs of Cl ions abreast, without in the least affecting the fall in potential per centimeter for a given speed of the ions. But the force will vary directly with the number of coulombs of ions we place abreast in the cross section and also with the speed of the current.

14. Electric Resistance.—The ratio of the fall in potential in volts to the current strength in amperes is the electric resistance in ohms (Ohm's law). Since, for a given length of conductor, the ratio of the voltage to the current velocity (which is the ratio of the force to the current strength) is a constant quantity at constant temperature, it follows that the resistance varies inversely as the quantity of electricity per centimeter length of conductor. Hence doubling the cross section of any kind of uniform conductor halves the resistance.

15. Gaseous Ions.—One reason for describing the elementary principle of electrolysis is that electric conduction takes place in gases, as air, much on the same general principle except that the molecules, atoms, positive ions, and electrons are moving about at high speeds between collisions and the whole action is very complex, the number of ions varying with the voltage. Nevertheless, positive ions move away from the anode toward the cathode, while electrons move in the opposite direction. As more and more molecules or atoms become ionized by losing electrons, the gas becomes more and more conducting, that is, its resistance decreases as the number of ions increases. This takes place so rapidly that an ignition spark or a lightning flash appears to form instantly.

There are a number of methods of making a gas slightly conductive for low potential differences by ionizing it by means of x-rays, ultra-violet light, a hot filament or a hot body, or the radiation from radioactive substances, as radium.

CHAPTER IV

CHARGING AND DISCHARGING BODIES

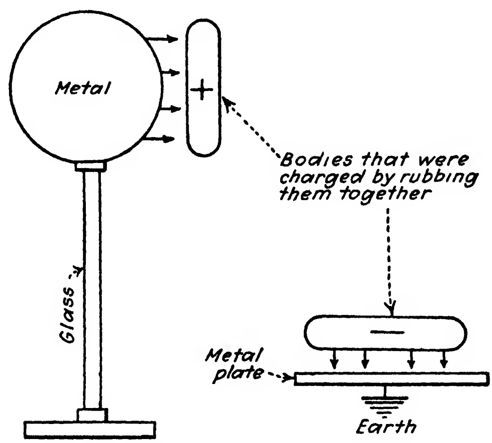
Electric charges may be regarded as evidences of unbalanced states of matter and can be obtained for practical use only by removing electrons from atoms, although large numbers of electrons are shot from the sun to the earth. A body is charged by either adding electrons to it or removing electrons from it, but no body can be negatively charged by rubbing until the charging electrons have been removed from some other body which is left positively charged. As surely as water tends to seek a common level so do electric charges of like kind tend to fall to a common potential, while unlike charges tend to neutralize each other. Some methods of obtaining charges of high potential are described in this chapter.

16. Charging Bodies.—Glass becomes negatively charged when rubbed with catskin, but positively charged when rubbed with silk. A strip of celluloid becomes negatively charged when drawn between the fingers. If two glass disks having different degrees of polish are rubbed against each other, the disk with the rougher surface will be negatively charged and the other will be positively charged. Metals become charged by rubbing when properly insulated. Charging bodies by chemical action is another example. Investigations made by J. J. Thomson and others seem to leave no doubt that the resultant charges due to friction and the like are due to the loosening of the connections between atoms—the valence electrons. When a piece of mica is rapidly split or friction tape is pulled apart in the dark, flashes of light are seen which are due to the recombination of the electrons with the positive ions from which they have just been separated.

The largest body available to us with which to share any charges that we may produce is the earth itself. The potential of the earth is taken as zero for purposes of reference, although it possesses a negative charge estimated at about 0.7 million coulombs. The surface of the earth is so great that the surface density of electrons is relatively very small, and the radius is very

large. Thus the earth not only is a good place to which we may discharge any electrons not wanted, or upon which to store electrons that may be needed later, but it also possesses a store of electrons upon which we may draw at any time.

Let us suppose we wish to positively charge a metal sphere without having any use for, or bother with, the corresponding negative charge. Then we can rub some electrons off one and onto a second body, thus leaving the first body positively charged. Let us connect a metal plate with the earth by means of a wire, although our own bodies may serve the purpose in many



A. Positively charging a metal sphere by attracting electrons from it. *B*. Discharging electrons to the earth.

Fig. 23.—Discharging the bodies which were charged by rubbing them together. The arrows show the directions in which the electrons move.

instances. Placing the positively charged body near or against the metal sphere permits electrons to leave the sphere and thus neutralize the charge on the rubbed body (Fig. 23), while the metal sphere thereby becomes positively charged. The negatively charged body may be caused to give its charge to the plate connected with the earth. Having discharged both bodies we can proceed to rub them together as before until enough electrons are drawn from the metal sphere to give it a good positive charge.

If we wish to give the sphere a negative charge, we can proceed as before, only this time we shall pass electrons from the negatively charged body to the sphere and draw electrons from the earth-connected plate to neutralize the positive charge of the rubbed body.

Frictional electric machines have long been employed for charging metal spheres and the like. It is important that all such apparatus be kept perfectly dry to prevent conduction of the relatively small charges at high potentials from the apparatus to the earth.

17. Electricity Conveyors.—We are so accustomed to thinking of closed electric circuits in connection with continuous currents that sometimes it is forgotten that electric currents may consist of joy-riding charges, as on belts. All that is required for that kind of an electric current is some means of producing a charge or charges and some means of producing a force that will move the vehicle upon which the charges ride. The most common type of

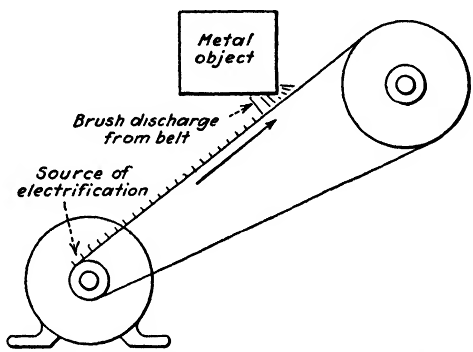


FIG. 24.—How metal objects become electrically charged by belts.

vehicle for joy-riding electric charges is a belt driven by an electric motor.

The friction of leather belts (which are fairly good electric insulators when dry) on pulleys often causes insulated metal objects, such as shelving and drums, to become so highly charged that one may receive annoying shocks of high voltage but of very small current strength when passing near them; sparks therefrom may ignite gases, and so forth. There are instances where potentials from such charges have caused the disruption of the electric insulation on the wires and frames of electric motors. Even when such belts pass from the pulleys of motors, for example, to metal pulleys connected to machinery, some of the charge passes from the belt to metallic or other conducting objects before reaching the metal pulleys (Fig. 24). Hence objects which are liable to become electrically charged in this manner are connected to the earth (or "ground") by a wire so that electrons may

move thereto if the charge is negative, or from the earth to neutralize the positive ions if the charge is positive. Another method is to remove the charge from the belt near the driving pulley by placing a ground-connected discharge (or collecting) wire brush over the belt to discharge it at the source and thus prevent objects from receiving any charge. Such charges also may originate at the driven pulley.

In cases where a belt of any kind removes electrons, these are carried from the source by the belt as a conveyor to form a very weak electric current surrounded by a very weak magnetic field. The air between said charges and metal objects becomes ionized and, therefore, conducting, so that a quiet discharge takes place between the belt and the metal objects, as the shelving or the wire brush connected to the ground. This is called a brush discharge. It is most pronounced between sharp points or edges. In refined apparatus all edges are rounded at as large a radius as practicable to prevent it. Hence balls or spheres are used where charges are to be conserved, especially where the potential is high, and points or sharp edges are used where electrons or ions are to be discharged and collected. If pointed wires are bent and pivoted, somewhat after the manner of one form of lawn sprinkler, and then connected to a highly charged body, or to an electric machine, the discharge of the electrons to the air not only will make an "electric wind" but also will make the device whirl around.

When positive ions are carried by a belt, they usually are ions of the belt itself, being molecules that have lost one or more electrons. Hence electrons pass from objects to the belt to neutralize the ions.

If an electrically charged belt runs to a pulley inside of a hollow metal sphere wherein it may or may not be necessary to employ a metal brush to deliver or collect the charges, the belt continually will convey charges from the source to the sphere, thereby charging the latter to a very high potential.

18. Oppositely Charged Bodies.—Let positive charges be produced on a belt by removing electrons therefrom. Then when the belt conveys these charges to the inside of a metal sphere in the manner previously described it will collect electrons from the sphere to neutralize the positive ions on the belt and in this manner the sphere will receive a strong positive charge.

Let a similar sphere be negatively charged by conveying electrons to it in the manner described. Then there will be two

metal spheres having opposite charges and, therefore, the difference of potential will be double the potential of either sphere if both are charged to the same, though opposite, potentials. When the spheres are widely separated the charges will have relatively little effect upon each other, but as they are brought nearer together, a force of mutual attraction will be in evidence which will be directly proportional to the product of the two charges and inversely as the square of the distance between their centers.

If the space between the two spheres is filled with castor oil (a liquid electric insulator or *dielectric*) instead of air, as by immersing them therein, the force of mutual attraction between them will be reduced to about one-fifth, the number 5 (approximately) being the *dielectric constant* of castor oil (that of vacuum and of air being unity), and the capacity of the system will be increased about five times.

Assuming the two spheres to be surrounded by air, if a discharge occurs through the air between them so that the electrons rush from the negatively charged sphere to the positively charged sphere (through the ionization of the air), when the spheres are 25 cm (about 10 in.) in diameter and their nearest points are 15.3 cm (6 in.) apart when the discharge occurs, the difference of potential between them is about 330,000 v or 330 kv, and if both were equally charged, the potential of each was about 165,000 v or 165 kv at the instant preceding the discharge.

Van de Graaff's high-voltage generator consists of two identical units. The original model will be described first. From a base, upon which is mounted an electric motor, projects a rod of pyrex glass 1.25 in. in diameter and 5 ft. high, at the top of which is mounted a copper sphere 2 ft. in diameter, with a pulley and collecting (or discharge) brush inside. A silk belt runs from the motor pulley to the pulley inside the sphere. A 10,000-v kenetron (Art. 181) set supplies unidirectional (rectified from alternating) voltage to the respective belts through a brush near the pulley of each motor. As electrons are removed from one belt, other electrons simultaneously are delivered to the other belt, the general action being as previously described.

Each sphere is thus rapidly charged to a potential of 750 kv, one being negatively and the other positively charged. Hence the total difference of potential between them is 1.5 million volts. When they are brought within 3 ft. of each other, the discharge

occurs (Fig. 25). Such apparatus, exclusive of the transformer and rectifier, are very inexpensive.

Van de Graaff's original generator produced millions of volts for the enlightenment of visitors at the Century of Progress Exposition at Chicago in 1933.

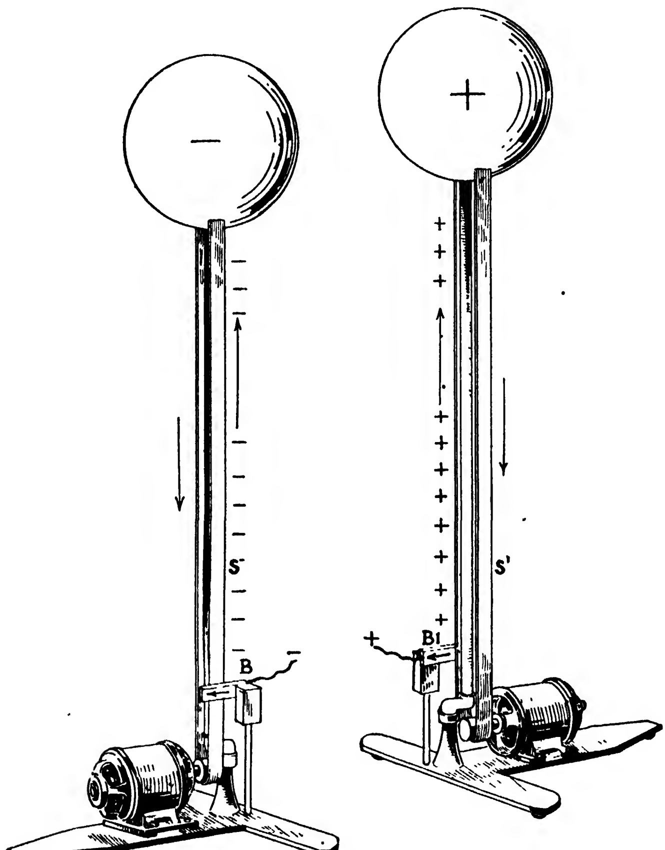


FIG. 25.—Principle of Van de Graaff's high-voltage generator as first demonstrated in the small 1.5 million-volt size S and S' are the silk belts. B and B_1 are the brushes, the arrows on which show the directions of electron flow.

Van de Graaff's generator, shown sketched from a photograph in Fig. 26, built at the Massachusetts Institute of Technology experiment station, was designed to deliver 30 to 40 kw at voltages from 10 to 15 million volts. Each sphere is a laboratory room, 15 ft. in diameter, within which the experimenters will work and operate the apparatus. These spheres are of polished

aluminum mounted on 30-ft. textolite insulating cylinders inside of which run the belts that carry the charges to the spheres. Each unit is mounted on a car or truck moving to and fro on rails so that the air-gap may be adjusted at will. One of the first

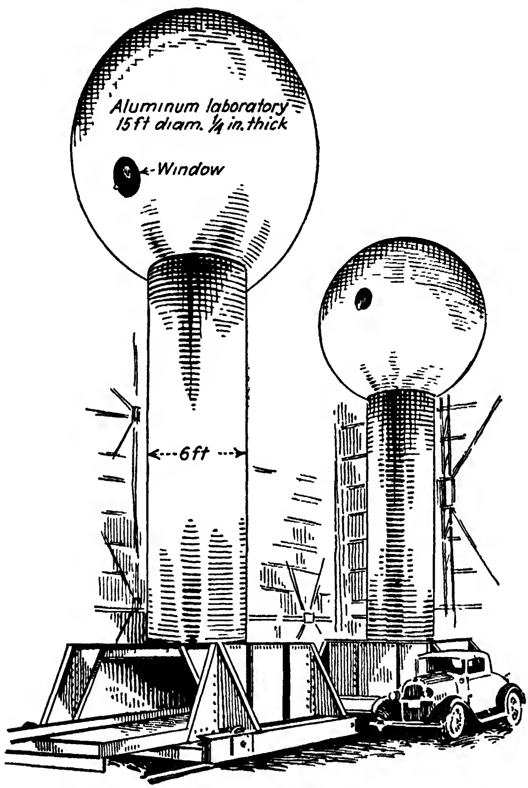


Fig. 26.—Van de Graaff's 10 million-volt generator.

jobs of this generator is the smashing of atomic nuclei. A large vacuum tube may be employed.

The apparatus just described is an example of what may be accomplished by going back to very old principles. Such high voltages also are required in studying the effects of lightning, as on transmission lines, by simulating it, for rapid and intense x-ray studies, and so forth.[1]

[1] More complete descriptions, by K. T. Compton, of this and other high-voltage generators will be found in the July 14 and 21, 1933, numbers of *Science*

19. Transfer of Charges from Sphere to Sphere.—When an uncharged metal sphere is brought near a negatively charged metal sphere, mutual attraction results due to influence (described in Art. 21). If both spheres are of the same size and they are attracted or otherwise are brought close together, one-half of the electrons will be crowded off the negatively charged sphere by their fellows and simultaneously will be attracted by the positive ions of the second sphere so that a discharge occurs, after which both spheres are negatively charged with mutual repulsion resulting between them. If one of the spheres is positively charged and the other is uncharged, mutual attraction will result through influence and electrons will be discharged from the formerly uncharged sphere, after which both spheres are positively charged, with mutual repulsion resulting between them.

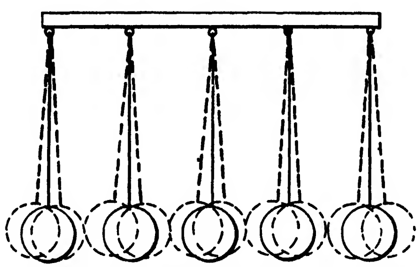


FIG. 27.—If any of the spheres is given a charge, the charge will be equally shared with its fellows.

If a series of such uncharged spheres of equal size are suspended as by silk threads and one of them is moved away from its neighbors, given a charge, and then released, the charged sphere will attract the nearest sphere through influence and communicate one-half of its charge thereto. The second sphere then will likewise transfer one-half of its charge to a third, and so on (Fig. 27), but the second sphere again will be drawn to the first further to share its remaining charge, and so on until all of the spheres have substantially equal charges. If all of the spheres actually touch each other, all will be equally charged. All spheres of whatever radii thus receive charges in direct proportion to their capacities so that they shall all be at the same potential.

When two equal spheres are unequally charged in any manner, though one be negatively and the other positively charged, it will be found that, after they have been brought into contact

with each other, their charges are identical in every respect and their potentials will be equal.

A small metal sphere (or a wad of paper covered with tinfoil) suspended as by a silk thread between the charged and uncharged

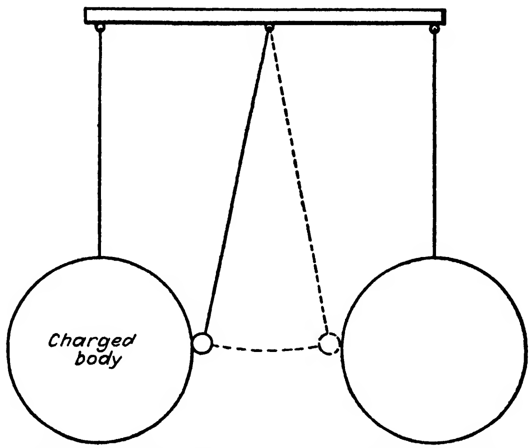


Fig. 28.—The small body progressively transferring one-half of the charge from a charged body to an uncharged body.

spheres (as hollow rubber balls covered with tinfoil) in Fig. 28 will oscillate to and fro as it alternately and periodically becomes charged and partially discharged, thereby representing a huge "heavy" ion. As the second sphere becomes more and more charged thereby, the small sphere retains more and more of its charge.

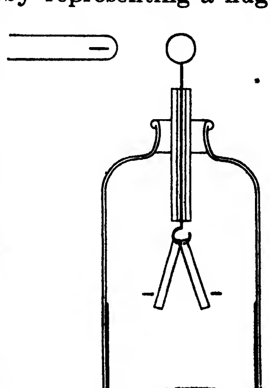
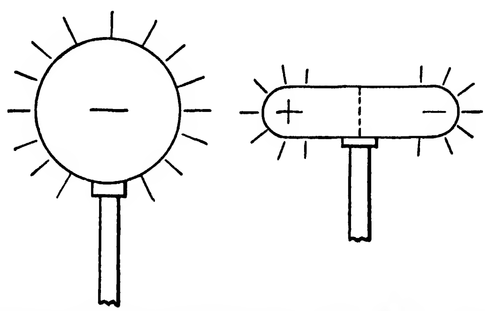


Fig. 29.—Electroscope.

20. Electroscopes.—While some of these instruments for detecting and measuring electric charges are extremely refined, only a simple form, easily made, herein is considered. That shown in Fig. 29 consists of a bottle or a jar of some kind with a paraffin stopper, through which runs a piece of glass tubing. Passed through the glass tube is a piece of brass or copper wire from which are suspended two strips of gold leaf. The ball at the top may be made of tinfoil. When given either a negative or a positive charge the leaves fly apart roughly in proportion to

the charge. A rubber comb rubbed on a cat receives a negative charge. If some of this charge is imparted to the electroscope the leaves will fly apart. Since the charge is known to be negative, another negative charge will cause the leaves to diverge still farther, whereas a positive charge will cause the leaves to fall together before again flying apart. In this manner the kinds of charges may be determined. Even such a simple electroscope must be kept very dry to prevent leakage of its charge. Many experiments with insulators and poor conductors,



A. Separation of valence electrons from the resulting positive ions in a metal by influence.

B. The separate halves retain their charges if separated under influence.

FIG. 30.—Effects of influence on metals.

as dry and moist silk threads, and also with very small charges, may be made with this simple device.

The very best electroscopes constantly are being discharged by cosmic rays which were discovered through this very effect, as explained in Chap. XXIV.

21. Influence.—If a suitably mounted sphere or ball is negatively charged and a sausage-shaped piece of metal, also mounted and insulated, is placed end-on near the charged sphere (Fig. 30), the end nearest the sphere will become positively charged and the farthest end will become negatively charged, but there will be no charge at its exact middle. The same general effect is obtained when the sphere is positively charged, but the charges of the conductor then are reversed. This effect was discovered by Canton in 1753.

Influence explains why electrically neutral or uncharged bodies always are attracted by either negatively or positively charged bodies, that is, by the charges on said bodies. In an electrically neutral body the valence electrons appear to be mutually shared, in a general way, by the respective atoms and molecules making up the body, that is, they occupy mean or natural elastically fixed positions in electric insulators or dielectrics, but can wander in metals. When a negatively charged body and an uncharged body approach each other, the valence electrons in the latter body are repelled and the resulting positive ions are attracted by the negatively charged body. The attracted positive ions then are nearer the negatively charged body than are the repelled valence electrons, resulting in a greater mutual attraction than repulsion. If a positively charged body is employed, the positive ions are repelled and the valence electrons attracted. Hence attraction always results until the bodies come into contact, or a discharge takes place between them through the air, when both bodies become similarly charged through the sharing of the charge on the charged body with the previously uncharged body, which always is immediately followed by mutual repulsion between them.

If the sausage-shaped conductor shown in Fig. 30 is made in two parts and then separated at its exact middle while under the influence of the charge on the sphere, and the latter then is removed, the half of the conductor that was nearest the charged sphere will be found positively charged and the farthest half will be found negatively charged, and thus they will remain until connected with the earth or some other body which will receive the surplus of electrons from the negatively charged half and restore electrons to the positively charged half, or they simply may be connected or touched together. It is obvious that only an exceedingly small proportion of the valence electrons move from one to the other of the halves of the whole metal conductor under the influence of the charge on the sphere; otherwise the respective charges would be enormous.

The force tending to separate the valence electrons and the positive ions is doubled when the metal to be influenced is placed between oppositely charged bodies (Fig. 31), which, if equally charged and spaced, causes the attraction due to either one of the charges to balance that of the other, and the forces of repulsion also are balanced. Hence there appears to be neither attraction

nor repulsion of the influenced body to tend to move it in either direction. If the potentials of the two opposite charges are increased, or the gaps between the spheres and the metal body influenced is decreased, electrons will be discharged from the negatively charged sphere to neutralize the positive charge on the influenced body and its electrons will pass to the positively charged sphere. Hence there is a transfer of electrons from sphere to sphere, but the electrons which leave the negatively charged sphere do not reach the other sphere during the discharge.

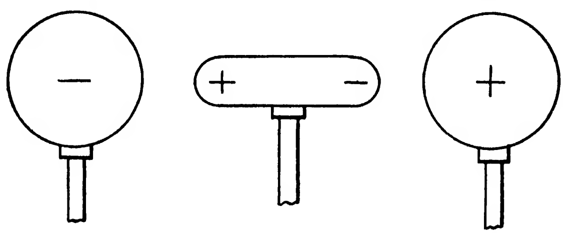


FIG. 31.—Doubling the influence.

22. Discharges through Wires.—When any charged metal body is connected with an uncharged metal body located some distance away from the former by means of a thin wire, the charge of the former body will be shared with the latter through the flow of electrons into one end of the wire and out at the opposite end. If the first body is negatively charged, electrons will be forced into that end of the wire, thus causing the free electrons therein to be shifted slightly due to the force of mutual repulsion between

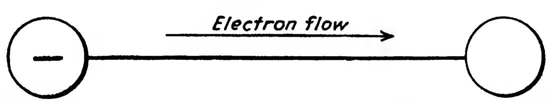


FIG. 32.—Direction of electron flow when a negatively charged body is being partly discharged.

all electrons, thereby causing some of the electrons formerly in the structure of the wire at its opposite end to be forced upon the uncharged body (Fig. 32). On the other hand, if the first body is positively charged, it has a deficiency of electrons upon its surface and, therefore, the positive ions on its surface will attract electrons from the wire. The positive ions in the wire, from which electrons were just attracted away, then will attract electrons from the other side of them, and so on, throughout the entire length of the wire, the positive ions at the extreme opposite

end of the wire attracting electrons from the uncharged body thereby giving it a positive charge (Fig. 33). The *effect* of influence travels at the speed of light through space but the electrons move very slowly in the direction of lowest potential in the wire. The effect of influence in a wire is increased by connecting it between two oppositely charged bodies (Fig. 34). Influence is what makes a wire conduct electricity when connected to a battery.

The flow of electrons constitutes an electric current due to a difference of potential, but without a closed electric circuit or

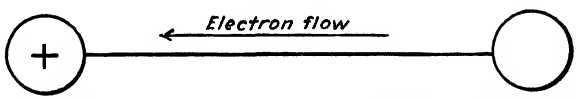


FIG. 33.—Direction of electron flow when a positively charged body is being partly discharged.

any appreciable influence between the two bodies, except through the medium of the wire. Such currents flow only in one direction when the resistance of the wire is sufficient to "damp out" or convert into heat the energy of the charge or charges by the time the difference of potential between the two bodies at the opposite ends of the wire is equal to zero. Otherwise the electrons oscillate to and fro as described below.

Since the moving electrons possess inertia, they tend to keep going right on after the difference of potential has fallen to zero. In the cases of Figs. 32 and 33 they thus tend to charge the second

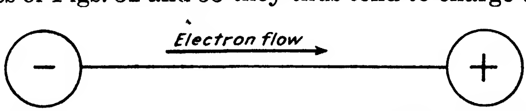


FIG. 34.—Direction of electron flow when two oppositely charged bodies are being partly or wholly discharged.

body to an increasingly higher potential, as the first body is positively charged through the withdrawal of electrons from it. Then the electric current ceases to flow for an instant and immediately thereafter proceeds to speed up in the opposite direction, and so on, to and fro like the swing of a pendulum, resulting in a loss of the energy originally imparted to the electrons in the wire through being partly converted into heat in the wire and partly radiated into space as radio waves until all of the energy is expended and there is no difference in potential between the spheres. This happens between even a small body

and the earth. It is substantially what happens in a vertical antenna, although there are other capacity effects due to the great surface of the earth and the proximity of the antenna thereto. It is a fundamental principle of all radio.

It is doubtful if the positive ions in solid metals take much part in electric conduction. Their masses are thousands of times greater than the mass of the electron; therefore, even if they did take part in conduction, their part could be neglected without introducing much of an error. Hence it is probable that, in the case of influence, only the valence electrons move through the structure of a metal, while the positive ions remain in the lattice[1] with the atoms, of which they are a part, not happening to be ionized all of the time. That electrons may be forced entirely out of metals by the forces of mutual repulsion between them and other electrons on charged dielectrics, by forcing the metal toward the charged dielectric, has long been known and is easily demonstrated, as described in the following chapter.

Experiments may be made with homemade apparatus wherein the so-called metal spheres may consist of any kind of ball covered with tin foil.

[1] The crystalline structure of matter or uniform spacing of the atoms.

CHAPTER V

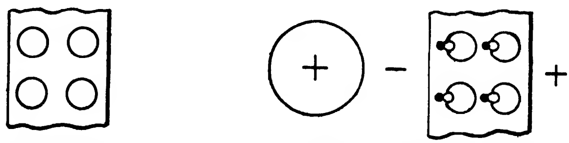
DIELECTRICS AND ELECTRIC CONDENSERS

All charged conductors that are free to move always move in such a manner that their potential shall decrease and their capacity increase. As noted in Art. 18, the presence of certain insulating materials or dielectrics further decreases the force of attraction and, consequently, the potential and increases the capacity. These principles are combined in the electric condenser wherein the metal conductors are plates placed very close together and whose surfaces may be made as large as desired, thereby making it possible to store relatively great charges of relatively low potentials, the energy being stored within the structure of the dielectric between its positive ions and valence electrons. A further means of charging bodies also is discussed.

23. Electrically Strained Dielectrics.—The valence electrons normally occupy such positions in the molecules of dielectric materials as to leave said molecules uncharged externally. Such molecules are represented as atoms in Fig. 35 for the sake of simplicity. When the dielectric is placed near either a negatively or a positively charged body, however, the dielectric exhibits a positive charge on one of its sides and a negative charge on the other side through influence due to the attraction of the positive ions and the repulsion of the electrons in the presence of a negative charge, and the attraction of the electrons and the repulsion of the positive ions in the presence of a positive charge. This tends to separate the valence electrons from the positive ions, when the dielectric is said to be strained, the actual strains occurring between the said ions and electrons which are elastically bound together through their mutual attractions.

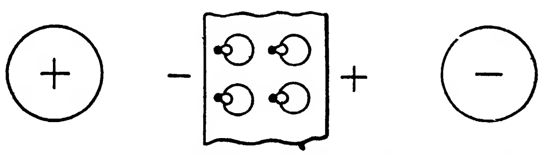
The force tending to remove the valence electrons from the positive ions is doubled when the dielectric to be influenced or electrically strained is placed between oppositely charged bodies (Fig. 35), which, if equally charged and spaced, causes the attraction due to either one to balance that of the other and also to balance the repulsions. Hence there appears to be neither attrac-

tion nor repulsion of the strained dielectric. If the potentials of the oppositely charged bodies are sufficiently great, electrons will be simultaneously attracted and repelled clear of the restraining positive ions, and eventually a discharge will take place through the dielectric which then is said to have broken down.



A. Normal or uncharged condition.

B. Effect of positive charge on molecules. The effect of a negative charge is just the reverse.



C. Doubling the displacement of the valence electrons.

FIG. 35.—Portion of a dielectric, indicating the effects of near-by charges.

It is customary to state that a dielectric placed between two oppositely charged bodies is strained in proportion to their difference of potential which then merely is the sum of their potentials. The greater the number of positive ions and the valence electrons elastically bound to them there are in a given volume of dielectric and the farther these electrons are moved or displaced from their mean or normal positions without being torn away, the greater is said to be the dielectric constant of the dielectric; that is, the greater is the amount of potential energy (force $\times$ distance) that can be stored within it for a given difference of potential between opposite surfaces.

The dielectric strength, or resistance to discharge due to the separation of valence electrons from positive ions, is much greater in many solid and liquid dielectrics than in air. Compressed gases also have high dielectric strengths.

When strains occur between electrons and positive ions which either separate them, as in metals, or tend to separate them in dielectrics, the electrons tend to return approximately to their former positions as soon as the source of influence is removed. There is this difference, however, that while the electrons bound to positive ions in dielectrics merely move back toward the ions,

the same electrons do not necessarily return to the same ions in metals wherein the electrons wander about. Thus while metals are best for conducting as well as for accumulating charges on their surfaces, dielectrics are the better for storing energy between charged metal bodies since the difference of potential between two such bodies may be relatively great at the same time that their charges are relatively small, due to the dielectric strength of the dielectric between them, or great charges may be stored with a low potential difference.

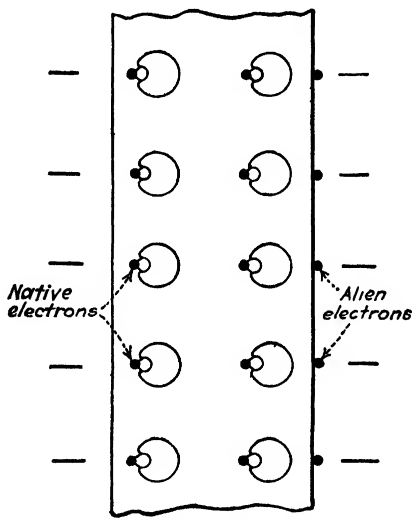
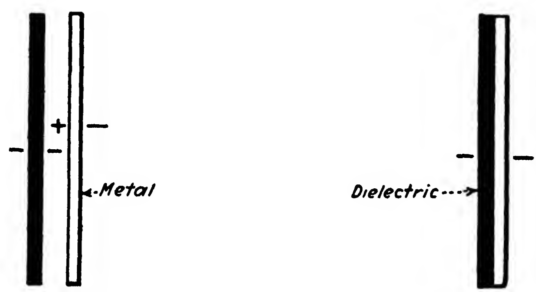


FIG. 36.—Effect of placing alien electrons on one surface of a dielectric.

24. Electrification of a Dielectric.—A thin hard-rubber disk, for example, may receive a negative charge on one of its surfaces by rubbing it with a catskin. For experimental purposes, the disk conveniently is suspended by a cord or otherwise mounted in an upright position. It is not necessary to insulate the disk because it is itself an insulator. The rubbing operation removes electrons from the catskin and transfers them to the surface of the rubber disk where, unlike electrons on a metal surface, they remain where they are placed. Then both sides of the disk are found to be negatively charged (Fig. 36). For purposes of identification, the structural or valence electrons of the hard rubber will be called *native* electrons and those obtained from the catskin will be called *alien* electrons.

When the surface of the dielectric (hard-rubber disk in this case) is charged with alien electrons, the balance between the positive ions and the native electrons is disturbed by the force of mutual attraction between the positive ions and the alien electrons and by the force of mutual repulsion between the native and alien electrons. As a result, the positive ions are slightly displaced toward the surface of the disk which is charged with alien electrons and the native electrons are slightly displaced toward the opposite surface of the disk, thus giving the latter a negative charge. This effect is different from that when the influencing negative charge is some distance away from the dielectric (Fig. 35).



A. Metal disk approaching the charged dielectric.

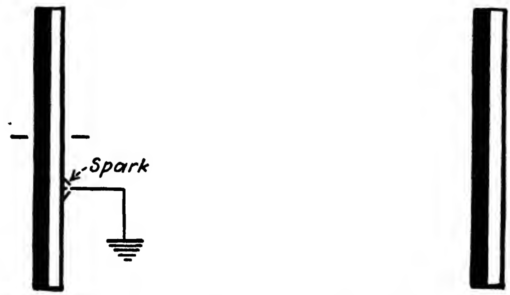
B. The metal disk is charged negatively on its outer surface, the adjoining charges on the two disks neutralizing each other.

Fig. 37.—Charging a metal disk by influence from a charge on a dielectric.

25. Obtaining Charges by Influence.—If a metal disk, for instance, of copper mounted upon an insulating handle of glass or sealing wax, is placed against either surface of the above charged hard-rubber disk (Fig. 37), but usually against the side charged with alien electrons, the electrons at the surface of the hard-rubber disk will repel the free electrons within the structure of the metal and will attract the resulting positive ions through influence. Since the metal disk really touches the hard-rubber disk at a very few points, it does not remove the charge thereon to any appreciable extent. The outer half of the metal disk then is negatively charged with the repelled free electrons, and the half nearest the rubber disk is positively charged due to the resulting positive ions (Fig. 37).

The metal disk may be discharged of its free electrons while resting against the rubber disk by connecting it to the ground

(Fig. 38) or merely by holding one's knuckle near it, in which latter case the free electrons will be forced to the knuckle by the alien electrons on the surface of the rubber disk and the free electrons will spread out all over the body. The discharge takes



A. Discharging the free electrons to ground.

B. After discharge, the entire combination shows no external electrification.

FIG. 38.—Effect of discharging the free electrons under influence.

place in the form of a spark of relatively high voltage but of small current strength.

The entire system now is electrically neutral, but work must be performed in removing the metal disk with its positive charge from the surface of the rubber disk, as potential energy thereby is stored between them—much as when a body is lifted against the force of gravity. The metal disk is electrically neutral after its free electrons have been discharged and while it still rests against the surface of the rubber disk, by reason of the mutual attraction of the alien electrons on the surface of the rubber disk and the positive ions of the metal. But when an attempt is made to remove the metal disk, the positive charge is very much in evidence (Fig. 39).

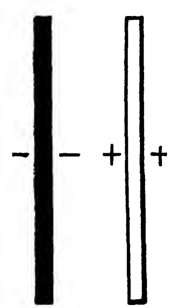


FIG. 39.—When the metal disk is separated from the dielectric after discharge, it has a positive charge.

Electrons are required to make the metal disk electrically neutral again; if one's knuckle is now placed near it, the electrons previously discharged therefrom, or some of them and others that happen to be about, will jump across the intervening air gap to the metal, when the latter again will become electrically neutral. The jumping of the electrons between the metal and the knuckle is not a simple phenomenon as it involves the ionization of the air, but the net result is as described above.

Volta's electrophorus, announced in 1775, consists of two parts, a round cake of resinous material cast in a metal dish (a hard-rubber disk usually is employed) and a slightly smaller round metal disk, or wood covered with tin foil, provided with an insulating handle. This is very convenient for obtaining electrical charges with which to charge other bodies, as the process described above may be repeated indefinitely.

Electric machines mostly operate on the principle of influence. The outputs of these machines are limited by the dielectric strengths of the insulating materials or dielectrics employed.

26. Dielectric breakdowns or ruptures of the insulation partly are due to heating (when the voltage is alternating or varying) and partly to the tearing away from their ions of valence electrons due to the strong forces electrically developed and by the breaking up of molecules by the impacts of electrons and positive ions. Thus small conducting channels are formed which widen and result in a complete breakdown of the dielectric material, which largely is a mechanical phenomenon.

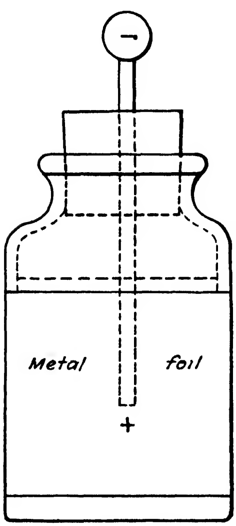


Fig. 40.—Leyden jar with salt (or sal-ammoniac) water as the inner electrode (−) and with metal foil or sheet (+) as the outer electrode. A carbon rod connects with the salt water. Either electrode may be positive or negative. Open-mouthed jars usually employ metal foil as the inner electrode and are the ones most commonly used.

Even the best dielectrics are very slightly conducting. In this connection, a resistor (high resistance) material may be thought of as partly conductor and partly dielectric and, therefore, must contain fewer free electrons per atom or molecule than has an electric conductor. Since the resistance of a conductor is inversely proportional to the number of free electrons contained therein, the higher the resistance the greater must be the speeds of the electrons for a given current strength (see Art. 14).

27. Electric Condensers.—The Leyden jar (Fig. 40) is the original form of electric condenser. Musschenbroek and his pupil Cuneus thought they would collect the "electric fluid" in a bottle. So they placed some water therein, passed a nail through the cork into the water, and then connected the nail to an electric

machine while holding the half-filled bottle in the hand. After its removal from the electric machine the student happened to touch the nail and received a shock. The surface of the water in contact with the glass was one electrode and the hand of the student was the other electrode. The glass was the dielectric between them. The same general effect is obtained by placing dielectric material between flat electrodes or plates of metal. Now we have radio and other types of electric condensers operating on this principle, although there are many forms of construction. The general principle follows.

If two conducting bodies are similarly charged, they will be mutually repelled and their respective potentials will be lowered because of the energy expended in moving them apart, but the capacity of each will be increased. If one is negatively and the other positively charged, they will be mutually attracted, their respective potentials will be lowered as they approach each other, and their capacities will be increased simultaneously.

It is obvious, therefore, that the nearer two oppositely charged metal sheets or plates are placed together the smaller will be their respective potentials and the greater will be their capacities for equal (but opposite) charges on each. The smaller their respective potentials the smaller becomes the difference of potential between them. The greater their surfaces the greater becomes the capacity or *capacitance* of the entire condenser, the latter term hereinafter being used instead of capacity since it refers to a joint capacity instead of an individual capacity. There is a surplus of electrons on one of the metal sheets and a deficiency of electrons on the other sheet. Figure 41 illustrates the general action in the solid dielectric of an electric condenser, which should be compared with Fig. 35*C*.

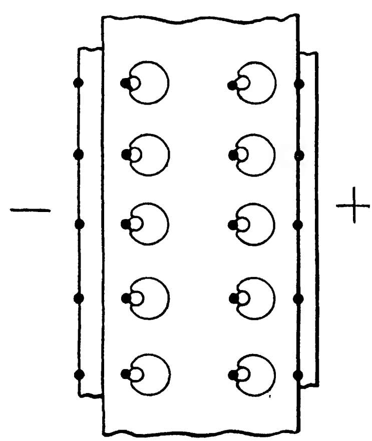
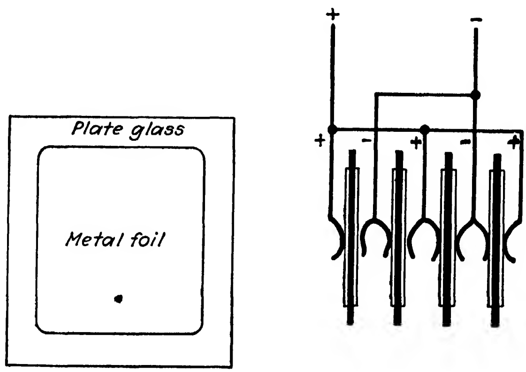


Fig. 41.—The strained dielectric of an electric condenser.

This combination is called an electric condenser (Fig. 42), not because of any condensation of electricity within it, but because no appreciable electric charges are apparent on the

outside of the connecting sheets or plates, between which the potential energy is stored. The inclusion of dry air between the plates has little effect on the capacitance, but the inclusion of a dielectric like mica or oil increases the capacitance for a given distance between the metal plates (of constant surfaces), either of which may be connected to ground without discharging the



A. A condenser unit. *B.* Units connected in parallel.

FIG. 42.—Single element of a high-potential plate-glass condenser with metal foil or sheet shellacked or otherwise fastened to either side, and a method of connecting the units in parallel. When the voltage is very high, two or more such (*B*) groups may be connected in series to keep the voltage across each group within the necessary limits. Connecting units in parallel increases the capacitance.

condenser when it is otherwise isolated. So long as there is no ionization (which is apt to occur with high voltage) of any kind between or near the plates, and so long as no electrons can get out of the metals, no electric current can flow between the plates even in vacuum.

All vacuum tubes are electric condensers fundamentally and the capacitances of such tubes have very pronounced effects on their operations.

CHAPTER VI

MAGNETIC AND ELECTROMAGNETIC EFFECTS

Magnets appear to consist of groups of atoms or molecules about which at least some of the valence electrons describe orbits or in which spinning electrons exhibit their magnetic properties, thereby surrounding them with magnetism, commonly called magnetic flux, which also permeates their structures. Hence all such atoms or molecules may be considered as miniature magnets. Electron-driving forces are electromagnetically produced within electric conductors while they are being linked or unlinked with magnetic flux, but at no other times. The more rapidly this takes place the greater is the force and, therefore, the difference of potential between the ends of the conductor. Thus bodies may be electrically charged, or electric currents may be caused to flow alternately and periodically to and fro in a closed electric circuit or between two bodies, as the plates of an electric condenser, but not continuously in one direction even in a closed electric circuit without rectification, by forces originating within the conductor itself due to changes in the linkage of magnetic flux with electrons of said conductor. Dielectrics also may be strained by this change in the linkage of magnetic flux with said dielectrics. Electric generators, motors, and transformers are the more important of the apparatus employing the principle. The story of magnetism, electromagnetism, and electromagnetic induction is briefly told in this chapter.

28. Magnets.—*Magnes lapis*, the natural magnet, was found by the ancients, notably at Magnesia in Asia Minor. This magnet stone attracted small pieces of iron. The Chinese knew of its directive power as early as A.D. 121. A thousand years later, Europeans rediscovered the directive power of the magnet or lodestone (leading stone)—the mineral *magnetite*—and suspended it from threads, floated it upon water, or placed it upon rafts floated on water, for use as a compass. Thus an early and useful application was found for the magnet, which has persisted to the present time.

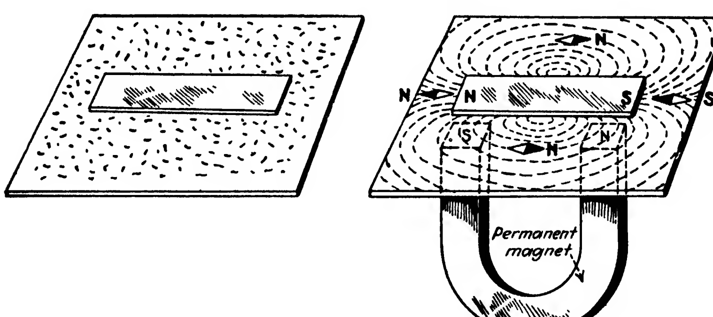
Peter Peregrinus wrote the first book on magnets, "Epistle on the Magnet," in 1269. He gave the name *poles* to the active parts of the magnet and also named them the *north* and *south* poles, respectively (a north pole, now called a north-seeking pole, pointed north), and showed that unlike poles are mutually attracted while like poles are mutually repelled, and that if a lodestone is broken in two, each half will have a north and a

A. Normal. *B.* Broken.

FIG. 43.—Bar magnet (or lodestone).

south pole (Fig. 43). Three hundred years rolled by with substantially no advance in knowledge about magnets. Then, in 1600, Dr. Gilbert experimented and wrote of a large number of discoveries in his work "De Magnete."

Artificial magnets could be made by stroking hard iron or steel with a lodestone, after which they exhibited the magnetic properties of the lodestone. Thus a magnetized needle evolved



A. Normal. *B.* Magnetized.

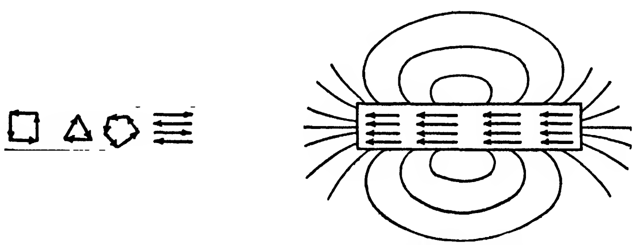
FIG. 44.—Effects of magnetic induction. The presence of the permanent magnet causes the soft-iron bar and the iron filings to become individual magnets. The compass needles show the directions of the induced magnetic flux.

into the present compass needle, magnetized bars became bar magnets, and so on. Such magnets are called permanent magnets, although their magnetism becomes impaired by heat, vibration, or by the repulsive actions of more powerful magnets. The most common form is the horseshoe permanent magnet.

While a lodestone or a permanent magnet will attract a piece of soft iron which becomes a magnet while it is under the influence

of the permanent magnet, it loses most of its magnetism when it is removed from said influence. The iron is said to be magnetized by *magnetic induction*, the term *influence* being reserved for electric charges. Hence magnetized soft iron is said to be a temporary magnet. Iron filings, however fine, thus become magnets when in the magnetic field of a magnet. Figure 44 shows the effects of a magnetic field on an iron bar, iron filings and compass needles through the phenomenon of magnetic induction.

29. Ferromagnetism is the phenomenon of magnetism in iron and steel. No matter how finely iron may be filed or pulverized, each particle becomes an individual magnet by magnetic induction and when such iron particles are placed together, as in a



A. Normal. *B*. Magnetized.

FIG. 45.—Explanations of magnetism in iron and other ferromagnetic materials. The normal (*A*) conditions are shown for a number of possible crystals and other arrangements, but only one form probably exists in any particular kind of ferromagnetic material.

tube, they all behave as one complete magnet. Hence it appears that the atoms or molecules of iron and steel are individual magnets.

In the absence of a magnetic field, as that of a permanent magnet, the molecules tend to form natural groups (Fig. 45). In the presence of the magnetic field of a magnet, however, they swing around like compass needles in the direction of the magnetic flux. As the strength of the magnetic field increases, they swing around more and more until, finally, they can turn no further when the ferromagnetic material is said to be magnetically saturated.

Thus magnetic flux "comes out" of a ferromagnetic material to join the magnetizing magnetic flux, the sum of the two magnetic fluxes being the *induction*.

Bitter recently suspended a magnetic powder in a liquid and then let the liquid evaporate on the polished surface of a piece of

the ferromagnetic metal cobalt. The groupings of the particles produced a regular lace-work appearance in the form of hexagons, which caused him to conclude that this was the arrangement of the blocks of atoms in the cobalt. When he magnetized the cobalt the pattern changed to a series of nearly parallel lines, just as they should according to the above theory. The fact that the lines were not exactly parallel was attributed to impurities in the cobalt.

30. Electromagnetism.—Electric currents were known toward the close of the eighteenth century and a connection between electricity and magnetism was suspected. Objects of steel, such as knives, had been known to have been magnetized by lightning, and attempts were made to magnetize steel by causing electric currents to flow in it and also by simulating lightning with strong

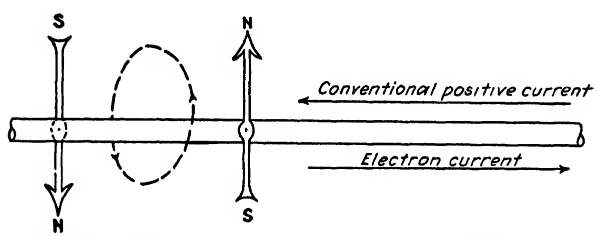


FIG. 46.—Oersted's discovery. The direction of the electron current also is shown for comparison.

electric discharges near it. But the problem was solved accidentally when a compass needle happened to be near a wire wherein an electric current was flowing.

Oersted was the fortunate man who made the discovery (1819) through his ability to grasp the significance of this seeming coincidence of the moving compass needle. He found that when the current flowed one way the needle turned or tended to turn in a certain direction at right angles to the direction of the current. If the direction of the current was reversed, or the wire was placed beneath (instead of above) the needle, the needle swung in the opposite direction (Fig. 46).

From the data obtained from Oersted's experiments, Maxwell suggested his "corkscrew" rule which, in effect, is as follows: "The relative directions of the current and the resulting magnetic flux are as the rotation and forward travel of a right-handed corkscrew." If the direction of the (conventional or positive—the reverse of the electronic) current is toward the cork, the

direction of the magnetic flux is clockwise, the magnetic flux existing in space about moving electrical charges or electric currents much as there also is electrostatic flux in space between electrical charges.

Iron filings sprinkled on paper surrounding a vertical current-carrying wire assume positions about as indicated in Fig. 47, showing that magnetic flux exists in space in the general forms of whirls about electric currents. It would seem like a simple explanation to say that this is due to spinning electrons, but no one can say that such is true at the present time, for nobody

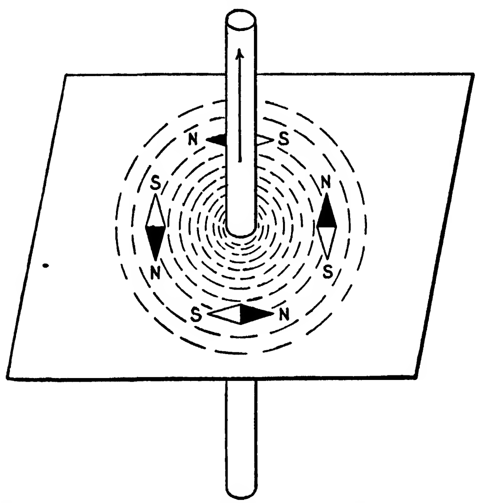


Fig. 47.—Explanation of Oersted's discovery. Filings and compass needles about the conventional positive current.

knows. The magnetic flux exists in all of the space surrounding the current-carrying wire throughout its entire length. Compass needles always tend to lie in the paths of magnetic flux and also to show its direction or magnetic polarity. Reversing the direction of the current also reverses the direction of the magnetic flux, but positive ions moving in a given direction produce the same magnetic effect as electrons moving in the opposite direction when the ionic and the electronic current strengths are equal. Thus there are magnetic fields about currents in electrolytes and in gases. The effect of reversing the direction of the current is shown in Fig. 48, wherein it is combined with that in Fig. 47. The strength of the magnetic field falls off with the distance from the current.

A negative charge moving downward produces the same magnetic effect as a positive charge moving upward. Hence we can represent the upward current as a positive charge moving upward or a negative charge moving downward, and *vice versa*, both of which are constant at the plane of the paper in Fig. 49

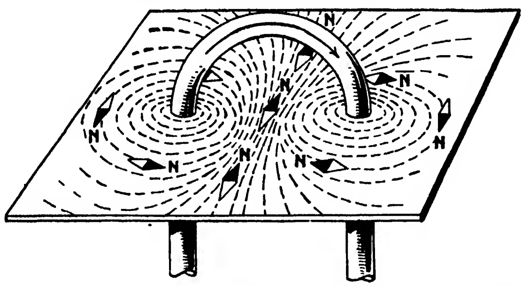


Fig. 48.—Effect of reversing the polarity of the current (right) and effect upon the polarity of the magnetic flux by looping the conductor.

when the current strength is constant, the electrostatic flux and the magnetic flux always being at right angles to each other, the former shown radially and the latter as circles.

Faraday gave the name "lines of force" to the lines representing the paths of both electrostatic and magnetic flux. Electrons and positive ions are at the respective ends of electrostatic lines

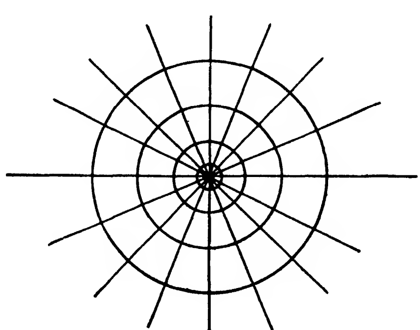


Fig. 49.—Electrostatic and magnetic flux paths about a single vertical current-carrying wire. The straight radial lines represent electrostatic flux. The circles represent magnetic flux.

of force which may be thought of as the ethereal fingers of the electrons searching through space to join those of the positive ions and pushing aside those due to other electrons in the way. Magnetic flux always exists in closed paths. No single magnetic pole ever has been discovered, although such poles have been

predicted, but the flux paths between the ends of a horseshoe magnet follow the same general contours as those between two charged bodies, as illustrated in Fig. 50.

The electromagnetic coil, or solenoid, was invented in 1820, when Arago and Davy independently magnetized iron and steel objects by placing them within helices of wire connected to electric cells, as in Fig. 51.

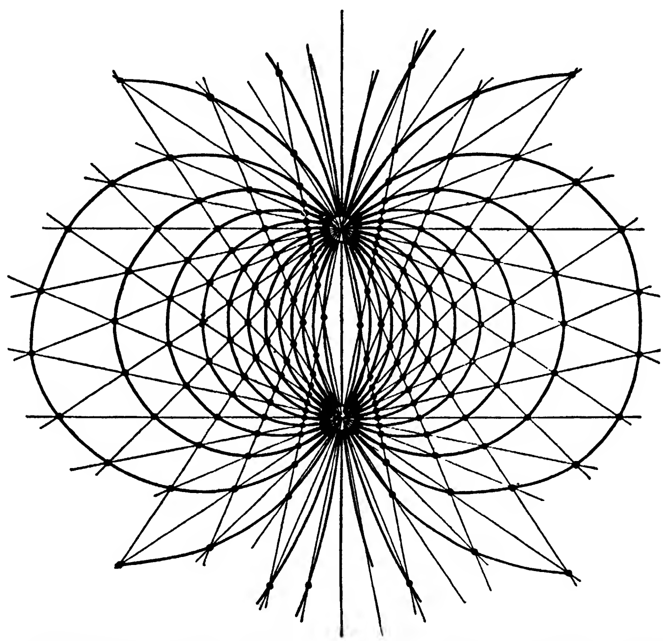


FIG. 50.—Method of constructing flux paths for either electrostatic or magnetic flux.

That a current-carrying coil, or solenoid, behaves like a magnet may be demonstrated by winding a number of turns of bell wire around a fountain-pen cap to form a helix and, after removing the formed helix, connecting the respective ends of the wire to a piece of copper and a piece of zinc which, when thrust through a piece of cork and floated in a drinking glass containing a 10 per cent solution of sulphuric acid, forms an electric cell producing an electric current in the helix capable of developing a magnetic field therein sufficient to cause mutual repulsion and attraction between its respective ends and the ends of a bar magnet (Fig. 52). The tendency of the current-carrying coil to turn in a

magnetic field is the fundamental principle of the electric motor and many other forms of electrical apparatus, as electrical indicating and recording instruments.

Sturgeon made the first electromagnet in 1825 by winding 18 turns of bare copper wire upon an insulated iron core about a foot long and half an inch in diameter, bent into horseshoe form. It was provided with an iron armature (Fig. 53). When connected to a single cell it sustained 9 lb., but as much as 50 lb. when more cells were used.

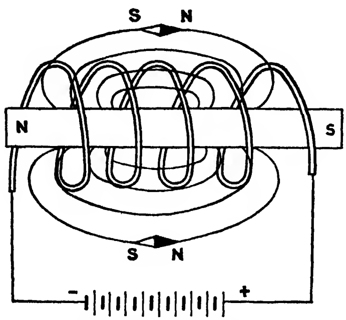


Fig. 51.—Magnetizing steel by placing it inside of a solenoid.

Although we deal with small currents, small forces, and relatively high voltages in the cases of charged spheres, we deal with great forces in the cases of electromagnets wherein the current strength may be great and the voltage low, or the voltage may be great and the current strength small, according to the

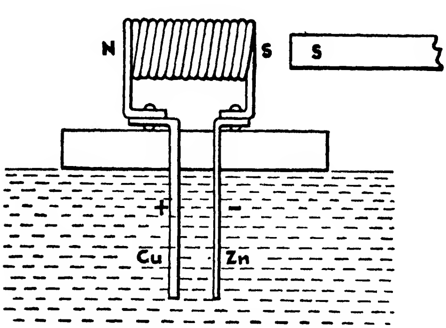


Fig. 52.

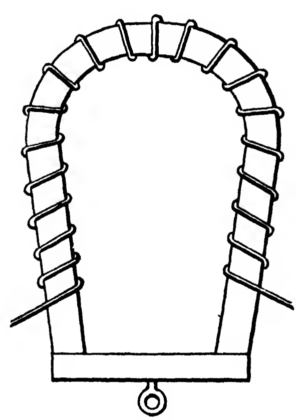


Fig. 53.

Fig. 52.—Floating solenoid being repelled by a magnet.
Fig 53.—Sturgeon's electromagnet.

number of turns employed. If the current strength is to be relatively great, we merely increase the cross section of the wire so that it will not get too hot.

Henry made the first practical electromagnet in 1828 by first insulating the copper wire by wrapping it with silk and then

winding the insulated magnet wire to form a coil of many layers and many turns per layer. Thus Henry made the first insulated magnet wire and wound the first practical electromagnetic coil. These inventions, like the match invented three years later, have persisted for more than a century—fundamentally unchanged. Henry's invention made possible the long-distance telegraph, for at that time others were unsuccessful in their attempts to transmit electrical energy to any considerable distance.

Now we have electromagnetic devices operating with extremely small current strengths and voltages, and so on, in increasing sizes up to huge lifting magnets sustaining loads weighing 30 tons or more. There is no limit to the force that may be developed between an iron rod and a solenoid, the only practical limit being the current strength the coil will carry without melting, since the force is proportional to the product of the magnetic flux produced by the current and that brought out of the iron. Hence, even after the iron is saturated with magnetic flux, the current strength may be increased indefinitely until the coil melts, the force increasing directly with the current strength after the iron is saturated.

There is no fundamental difference between a magnetized piece of iron and an electrically energized coil of copper wire so far as the electromagnetic action is concerned. An electron describing a closed orbit in space is a minute magnet. The function of an electric conductor also is to guide the free electrons therein and make them move, in the aggregate, in near-circles. The electrons describing orbits about the "hearts" or central nuclei of atoms produce magnetism; therefore, atoms also are electromagnetic in character. Electrons undoubtedly are associated with iron atoms in such a manner that said atoms are minute magnets (Fig. 54) which form closed magnetic circuits (Fig. 45) when undisturbed by an influencing magnetic field and, therefore, exhibiting no external magnetic field of their own.

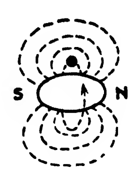


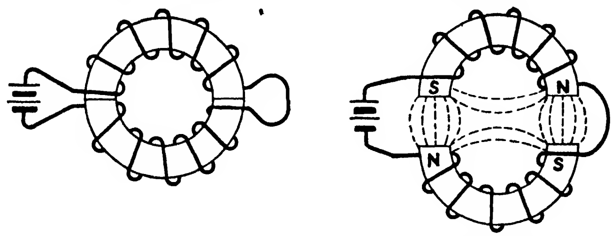
Fig. 54.—Analogue of an iron molecule.

The fact that thousands of times as much magnetic flux may be produced by a given current strength in a coil when a ferromagnetic material such as iron is inserted therein makes it proper to call a ferromagnetic material a magnetic-flux amplifier.

Much as atoms may exhibit no external electrostatic field until electrons and ions are pulled apart, so also do closed mag-

netic circuits exhibit no external magnetic field until pulled apart. This is illustrated in Fig. 55.

31. Electromagnetic Induction.—Faraday and Henry independently discovered that tremendously important phenomenon which makes electric power generation, transmission, distribution and utilization possible. Faraday discovered it in 1831,

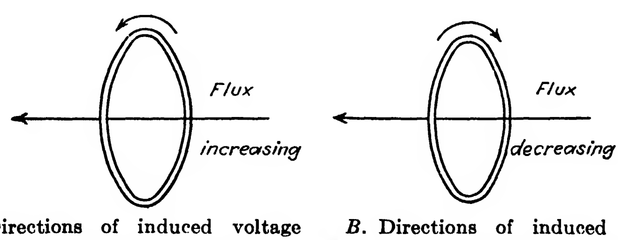


A. No appreciable external magnetic flux.

B. When separated, the external magnetic field appears.

FIG. 55.—Closed and partly opened magnetic circuits.

Henry in 1832. Faraday could not call up Henry on the transoceanic radio telephone in those days, and, therefore, Henry knew nothing about Faraday's discovery until after he had discovered the same thing. Since the discovery was made, however, news of such discoveries are diffused all over the world in a short time through this very discovery. Faraday and Henry found that *while* a conductor is being linked or unlinked with



A. Directions of induced voltage and positive current tending to demagnetize.

B. Directions of induced voltage and positive current tending to magnetize.

FIG. 56.—Effects of varying the magnitude of the magnetic flux linked with a conductor.

magnetic flux, a voltage is produced or induced in the conductor, the direction of the voltage during the increase in linkage being opposite to that produced during the decrease in linkage.

The general effects are illustrated in Figs. 56 and 57, wherein it is observed that when the linkage is increasing the induced voltage acts in such a direction as to produce a demagnetizing

current, that is, to slow down the magnetizing current. Thus it acts in such a way as to tend to resist the increase in the linkage when the linkage is increasing, and when the linkage is decreasing it acts so as to tend to increase the linkage—tending to resist the change in both cases.

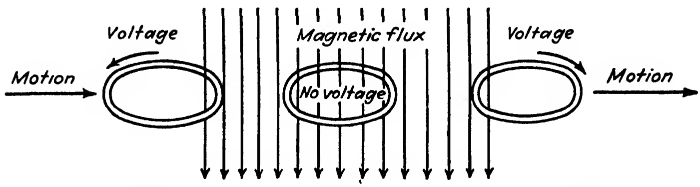


FIG. 57.—Effects due to moving a closed turn of conductor into, through, and out of a magnetic field. The direction of motion is only incidental to linking and unlinking.

If an attempt is made quickly to force a fairly thick disk or sheet of copper (which in this case forms a closed electric circuit) between the poles of a powerful magnet (Fig. 58), much force is required. This force operates through the medium of the magnet to move the free electrons in the copper to form an

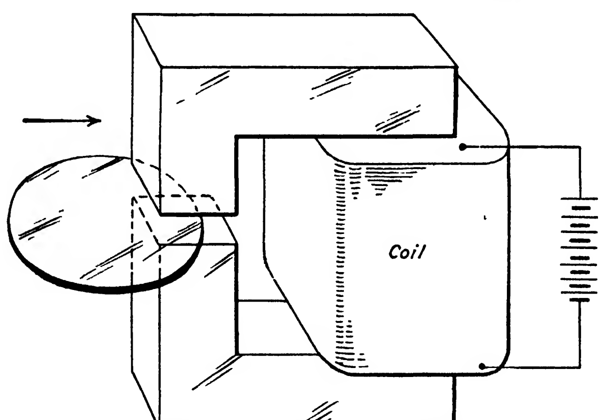


FIG. 58.—Force is required to push the disk rapidly between the poles of the electromagnet.

electric current therein, the direction of the current always being at right angles to the direction of the magnetic flux and, therefore, flowing in closed circles. These general kinds of currents as produced in a copper sheet are called eddy currents because they are in forms of whirls or eddies. An application of this principle

is found in the watt-hour meter in every wired building, wherein the disk revolves between the poles of magnets, much as in Fig. 59, to act as a drag on the mechanism to prevent its speeding up or accelerating.

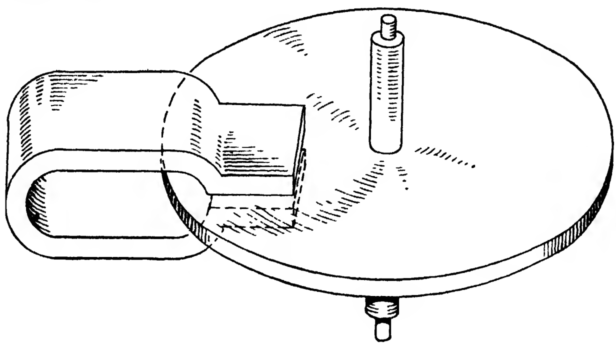


FIG. 59.—Principle of the watt-hour meter drag magnet and disk. See also Fig. 69.

32. Self-induction.—When an attempt is made to start a current flowing, particularly in a coil of wire linked with iron or steel, the magnetic flux produced by the current increases the linkage of magnetic flux with the turns of wire, thus establishing or inducing a counter-voltage in the wire tending to prevent the

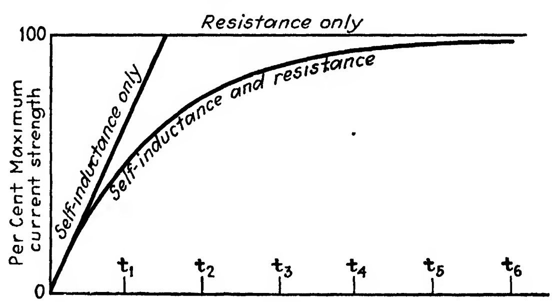


FIG. 60.—Effects of self-inductance and resistance in a constant-voltage circuit. The curve showing the growth of current strength with both self-inductance and resistance present is the exponential or law-of-organic-growth curve, the current growing to 50 per cent of its maximum strength in time t_1, to 75 per cent in time t_2, then to 87.5 per cent in time t_3, and so on, always growing half-way between its value at any of these times and the maximum current strength in equal times.

increase in the linkage of electric current and magnetic flux. This phenomenon is termed self-induction, the coefficient of which, that is, the ratio of the self-induced voltage to the time rate of change in the current strength, is the self-inductance or

electromagnetic inertia of the current. The self-inductance per turn is the ratio of the magnitude of the magnetic flux to the current strength.

Hence a current driven by a constant voltage, like that of a battery, tends to speed up uniformly, gaining equal speeds or strengths in equal times, so that if there was no electric resistance in the circuit, the current strength eventually would become extremely great. However, electric resistance is present in every circuit, so that the current strength eventually reaches a maximum as limited by the resistance of the circuit. Practically, this may take place in a small fraction of a second.

Figure 60 shows how the current strength tends to increase as time elapses and how it actually increases due to the effects of self-inductance and resistance combined.

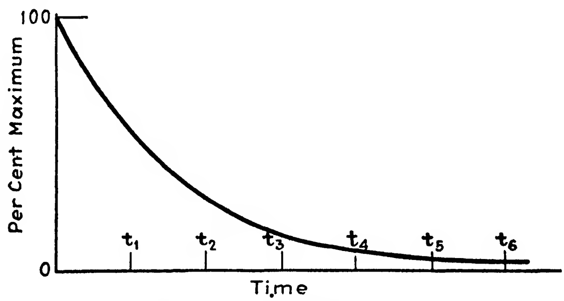


FIG. 61.—Die-away curve.

Self-inductance bears substantially the same relation to mass that voltage bears to force in so far as their actions are concerned, but both self-inductance and voltage are independent of the number of actual masses of electrons placed side by side, that is, upon the number of conductors connected in parallel. The self-inductance of a straight wire varies directly as its length, one unit of self-inductance being the centimeter.

When both of the exponential curves in Figs. 60 and 61 are expressed in percentage, either results from subtracting the values of the other from 100. The curve in Fig. 61 shows the current strength at different instants when a condenser is being charged from a battery with resistance in series.

33. Mutual induction results when two independent circuits react upon each other so as to be coupled together with a magnetic or transformer coupling. The coefficient of mutual induction is termed the mutual inductance of the two circuits. The

mutual inductance between two electric circuits mutually linked with a common magnetic circuit is equal to the change in the number of magnetic linkages in either circuit per unit change in the current strength of the other circuit, or that quantity by which the time rate of change in the primary current strength must be multiplied to give the secondary voltage; that is, it is the ratio of the secondary voltage to the time-rate of change in the primary current strength, wherein the primary circuit is that in which the magnetizing current flows or that circuit including the source of electrical energy.

CHAPTER VII

ALTERNATING CURRENTS

The fact that the direction of the induced voltage during the linkage of magnetic flux with turns of electric conductor is opposite to that during their unlinkage makes it possible to generate alternating currents of any desired strength and voltage, limited only by the cross section of the current-carrying conductor and the dielectric strength of the insulating material employed. Through mutual induction the voltage is stepped up and the current strength is proportionately decreased through the medium of a transformer, or transformers, at the generating station so that the heat losses in the line shall be small and the line less costly. At the distribution centers the voltage is reduced through transformers and, finally, it is further reduced for lighting and other purposes. Smaller transformers still further reduce, or else step up, the voltage for use in radio receiving sets and the like. This chapter deals with the principles of the production and utilization, as well as the characteristics, of alternating currents.

34. Production of Alternating Voltages.—The fundamental principle of the practical electric generator is shown in Fig. 62, the voltage wave produced thereby being illustrated in Fig. 63. The greater the speed of rotation of the loop the greater is the frequency or number of complete cycles per second and the greater is the voltage. For a given magnitude of magnetic flux and number of turns of wire the voltage varies directly as the frequency.

In 1856, Siemens wound some wire on a piece of iron and rotated this "armature" between the poles of a magnet, thereby producing an alternating voltage. When this was connected in an electric circuit an alternating current flowed therein. While earlier attempts had been made by others, as described in Art. 38, this machine was the forerunner of the magneto used for ignition, in telephony, and so forth.

Large electric generators employ electromagnets for producing the field of magnetizing magnetic flux whereby alternating

voltages are produced in their armatures through rotation. Sometimes the armature rotates and sometimes the field revolves, as in the large turbine-driven generators. In any event, the stationary part of a generator is the stator and the rotating part is the rotor.

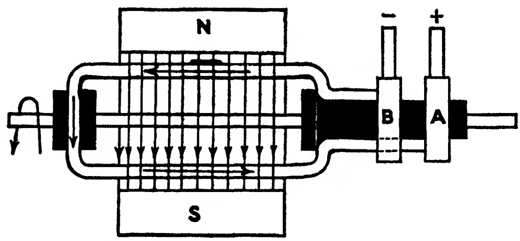


FIG. 62.—The induced voltage is maximum when the linkage is changing from zero to a finite value, and *vice versa* The black mark on the conductor under the *N* identifies that part of the loop in the following illustration.

35. Effects of Self-inductance.—If only electric resistance were present in an alternating-current circuit, the current would reverse when the direction of the voltage reversed, both reaching their maximum and zero values at the same instant. The free electrons move only when they are pushed along and stop going the instant the force is removed because of the electric friction of the conductor; at least that is the way the electrons appear to

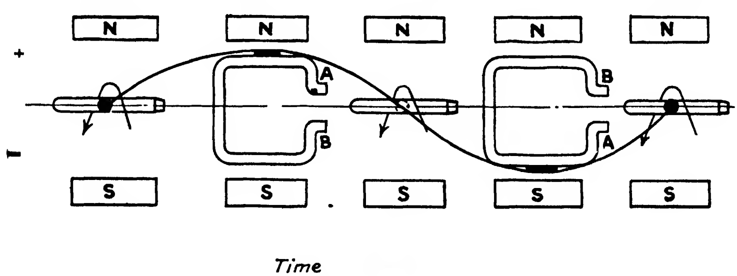


FIG. 63.—The sinuous sinusoidal or sine curve shows the magnitude and direction of the induced voltage at different instants produced by alternately and periodically linking and unlinking magnetic flux with turns of conductor through rotation.

act. But there always is some magnetic flux linked with electric currents. It is true that coils may have one-half of their turns wound in a direction opposite to that in which the other half are wound so that their currents tend to prevent the formation of magnetic flux, and the self-induced voltage of each half will

balance that of the other, but the connecting wires contain self-inductance. Likewise, all circuits contain some resistance.

When the resistance is so small with respect to the self-inductance in a circuit that it may be entirely neglected, the voltage alternately and periodically is expended in speeding up and slowing down the current. When once started in either direction, the current, by reason of its inertia, tends to keep right on flowing in that direction. The alternating voltage thus is kept busy in first getting the current started; then turning around

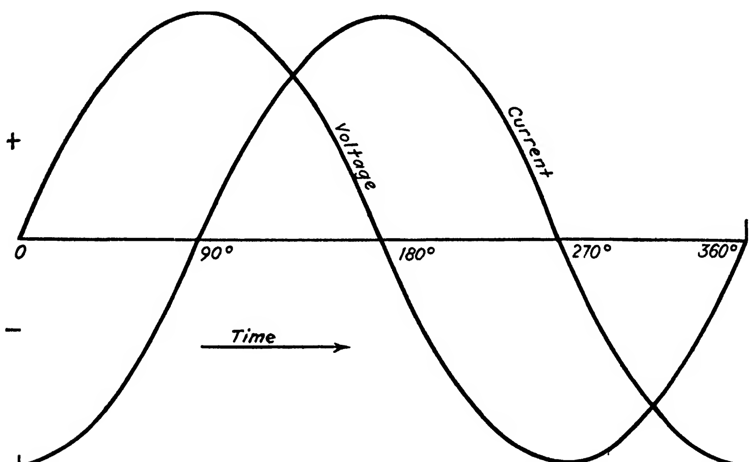


FIG. 64.—In an alternating-current circuit containing self-inductance wherein the resistance is so relatively small that it can be neglected, the current strength is 90 deg. "late," that is, it lags 90 deg. behind the impressed voltage.

and stopping it; getting it going in the opposite direction; and then stopping it again, all of which takes time.

As a result, the voltage is a maximum when the current strength is zero, and *vice versa*, as in Fig. 64, the current being said to lag behind the voltage by 90 deg.

36. Reactors.—A coil of wire, helix or solenoid, with or without a ferromagnetic core (such as iron), is a device which reacts on alternating voltages by setting up self-induced voltages which would equally oppose them if there were no energy losses in the copper, iron, or insulation, the current strength varying inversely as the maximum linkage of magnetic flux with turns of wire. If the maximum linkage is large, the current strength is small, and *vice versa;* hence the smallest current strengths for a given

frequency and number of turns of wire occur in reactors having closed ferromagnetic circuits.

The unit of magnetic flux is the *maxwell,* so named in honor of the great physicist. When 100 million maxwells are linked with 1 turn of wire and the linkage is destroyed uniformly and completely in 1 sec., there is a difference of potential of 1 v between the ends of that turn during the entire second.

We can "bring out" as many as 120,000 maxwells of magnetic flux for each square inch of cross section of a closed ring or rectangle of iron by winding turns of insulated wire around it, or by winding a coil and then placing iron within it, and by causing a relatively small current to flow in the wire. The product of the number of turns of wire and the current strength in amperes flowing in them is the number of ampere-turns. We can increase the number of turns and decrease the current strength without affecting the number of ampere-turns so long as their product is kept constant and, therefore, without affecting the magnetization of the iron. If there is an air-gap in the magnetic circuit, we must employ many more ampere-turns to fill the gap with magnetic flux or, what is the same thing, to force the magnetic flux across the gap.

The product of the number of turns of wire linked with the iron and the number of maxwells of magnetic flux in the iron is the number of flux-turns or maxwell-turns. Hence the induced voltage will be 1 v when the time rate of uniform linkage or unlinkage is 100 million maxwell-turns per second. An induced voltage of 10 v requires that 1 billion linkages change every second, and so on. If the time rate of linkage or unlinkage is not uniform over a given period of time, then corrections must be made to obtain the *effective* voltage over that period, as during one cycle, one second, and so on.

Let us punch out from some thin sheets of transformer "iron" (such as silicon steel) a number of rectangles or laminations, cut across at one corner so that they can be slipped into a coil, and then stack them up inside a coil and clamp them together to form a reactor (or else a transformer) core (Fig. 65). We use thin sheets to reduce the eddy currents formed in the iron itself due to the voltages induced in it, since iron is a conductor, even though a rather poor one. The iron will become hot enough due to the swinging to and fro of its molecules as the current alternates, without its being heated by induced currents.

If we keep the magnetic flux density of the iron down to about 45,000 maxwells per sq. in. and the current density in the copper wire linked with it to about 1,000 amp. per sq. in., we should get along without too much heat being developed.

When an alternating current flows in the turns of the coil shown in Fig. 65, the current strength will rise from zero to a maximum in the positive direction; then fall to zero; next rise to a maximum in the negative direction; and then again fall to zero, thus making four complete changes—two linkages and two unlinkages—in the number of flux-turns during every cycle. As a result, it can be shown that we must have 15.9 million maxwell-turns per effective volt when the frequency is 1 c per sec.; 265,000

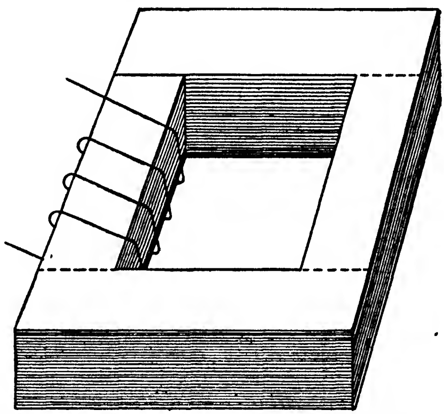


FIG. 65.—Built-up iron (as silicon-steel) transformer core.

maxwell-turns for 60 c; 15.9 for a million cycles, and so on, for each effective induced volt, the required number of flux-turns falling off as the frequency increases. Thus, while much iron may be required for low frequencies, no iron at all is required for the high frequencies of radio.

Let us make our unit iron rectangle 1 sq. in. in cross section and keep its maximum induction at 45,000 maxwells. Then 0.00283 effective volt will be induced in each turn of wire linked with the magnetic flux for each cycle per second of frequency. If the frequency is 15 c per sec. the induced voltage will be 0.0425 effective volt per turn; if 25 c per sec, 0.0708 effective volt per turn; if 60 c per sec. (ordinary lighting circuit), 0.17 effective volt per turn, and so on.

Now we have two ways of varying the effective induced voltage. One is to change the number of turns and the other is to change

the cross section of the iron, that is, we can use two or more of our unit rectangles as a single core. Changing the number of turns also means changing the cross section of our copper wire if we are to keep the current density therein constant. If we increase the number of turns, we use a smaller wire. If we decrease the number of turns, we use a larger wire. Hence we do not change the dimensions of our coil very much by changing the number of turns, except that we have to put in more insulation as we increase the voltage between adjacent layers of wire.

Let us stick to the standard frequency 60 c per sec. and 1 turn per effective volt. The maximum voltage during any half-cycle is 1.41 times greater than the effective voltage, and it is the maximum or "peak" voltage that breaks down electric insulation or dielectric materials. Thus the insulation between two conductors with a difference of potential of 110 effective alternating volts between them alternately and periodically is strained by 156 v.

If we want 110 effective volts to be induced in our coil and we want to use 110 turns of wire, then we shall have to make the cross section of our core 5.9 sq. in. But we can juggle the copper and the iron until we get the most economical combination for our requirements, consistent with overall dimensions, and so forth.

37. Transformers.—If we connect our coil to an attachment cord and plug it into a 110-v (usually 115-v), 60-c lighting outlet, we know we are getting a maximum of 45,000 maxwells per sq. in. of core, or 265,000 maxwells altogether in the 5.9 sq. in. of iron, alternately and periodically being linked and unlinked with the 110 turns of wire in the coil. The induced voltage almost exactly balances the lighting-circuit voltage, there being some voltage lost in heating the wire and iron. Hence, if we want to obtain a smaller effective voltage, all we have to do is to wind the required number of turns around the core, either over the first coil after insulating it, or on some other portion of the rectangle (Fig. 66).

We shall call this the secondary coil and the first the primary. Then if there are 110 turns in the primary coil and we want, for example, 12 effective volts in the secondary, all we have to do is to wind 12 turns of wire to form the secondary coil. Article 33 also should be read in connection with this effect. The ratio of the number of secondary turns to the number of primary turns is called the ratio of transformation, or turn ratio, and is the ratio of the secondary to the primary voltages. In this manner

voltages are said to be either stepped up or stepped down. If the cross section of our core and the frequency are such that when we have 110 effective volts across the primary coil and it consists of, for example, 100 turns, and we want 100,000 effective volts in the secondary coil, the ratio of transformation will be 909; therefore, we wind on 90,900 turns to form the secondary coil, but we divide it into a number of sections so that the voltage per section will be manageable.

The secondary current at any instant flows in a direction opposite to that in the primary coil, the primary current tending to magnetize the iron and the secondary current tending to

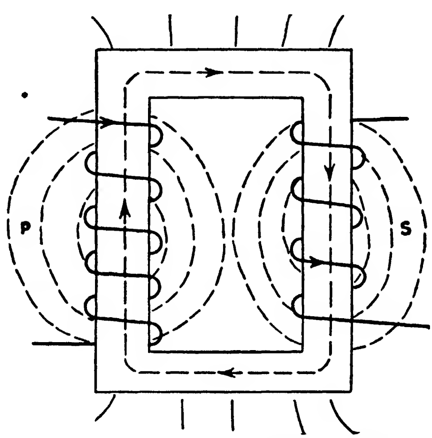


FIG. 66.—Core-type transformer showing magnetic leakage due to the demagnetizing action of the secondary current. Either coil may be the primary.

demagnetize it. Hence, when a load is placed upon the secondary coil, the secondary current tends to demagnetize the core, with the result that the self-inductance of the primary coil is instantaneously lowered and more current flows therein to keep the iron magnetized. Thus the iron tends to be magnetized to the same extent at all loads. Consequently short-circuits of the secondary coil also cause the equivalents of short-circuits in the primary coil when the primary and secondary coils are wound one above the other concentrically on the same leg of the core.

When the primary and secondary coils are wound on separate legs of the core, the ends of the rectangle in Fig. 66 have magnetic poles which alternately and periodically change from N to S, and *vice versa*, and the leakage of magnetic flux from end to end tends to give the primary and secondary separate additional

magnetic circuits. When the secondary coil is short-circuited under these conditions, the portion of the core within the primary coil is not demagnetized so much as that portion within the secondary coil, with the result that so much current does not flow in the primary coil under short-circuit conditions as when the primary and secondary coils are wound concentrically on the same portion of core. This is said to be due to leakage reactance.

There are many cases where this leakage reactance is necessary or desirable. In such cases it is magnified as in Fig. 67, wherein

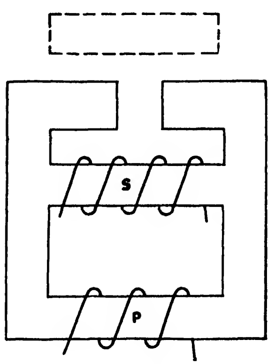


Fig. 67.

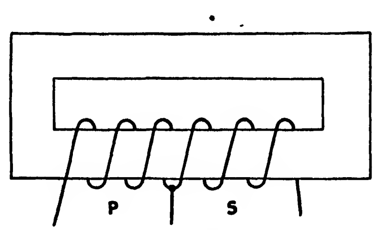


Fig. 68.

Fig. 67.—Leakage-reactance transformers reduce short-circuit effects and cause the secondary to behave like a reactor.

Fig. 68.—Autotransformer.

the dotted armature may or may not be used to adjust the leakage reactance. The latter effect has been taken advantage of in moving the armature to perform work. The primary of such a transformer may be permanently connected to a lighting circuit, for example, and when the secondary is closed, as by means of a push button or relay contacts, the armature will be attracted to strike a gong or to close a pair of contacts to control another circuit.

An autotransformer fundamentally contains a single coil with taps so that any portion of it may be used as a primary and any other portion as the secondary coil. Thus an end terminal may be common to both the primary and the secondary coils. This is shown schematically in Fig. 68.

The magnetic attraction and repulsion between parts of a transformer often produce much humming unless the laminations are tightly clamped and other precautions are taken.

38. Electric Generators.—Gambey had noted in 1824 that when a compass needle oscillated over a piece of metal, it came to rest sooner than over wood. Arago rotated a copper disk in its own plane beneath a compass needle. The needle was dragged around with the disk. A copper disk suspended over a rotating magnet was dragged around by it—the same as in the speedometer of one's car except for details of design.

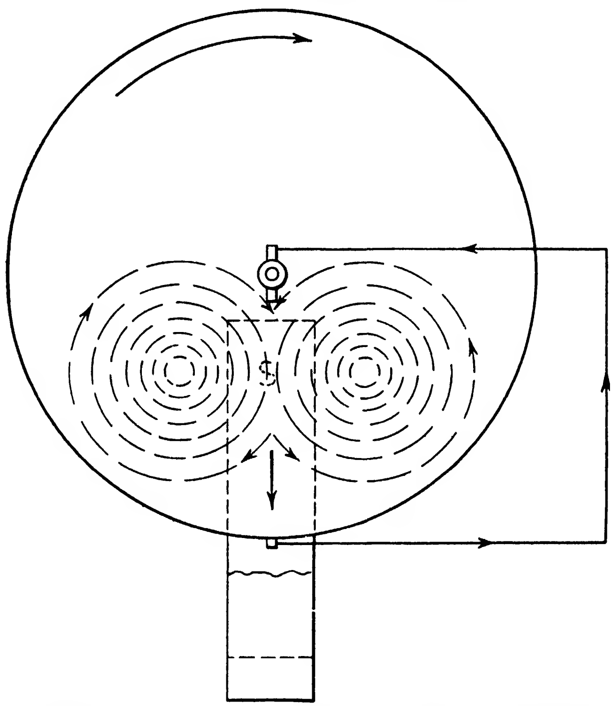


Fig. 69.—Faraday's direct-current generator Eddy currents are formed on each side of the poles of the magnet. The current is "drawn off" from axle to rim of the disk at the places of common direction of flow of the eddy currents.

Faraday built the first electric generator in 1831, but, while it worked on the principle of electromagnetic induction, it did not work like the electric generators of to-day nor like the practical electric generators which followed his discovery. His generator consisted of a permanent magnet, between the poles of which rotated a copper disk (Fig. 69). This delivered a direct current from shaft to rim, or *vice versa*, according to the direction of rotation of the disk. It was the forerunner of the magnet-and-rotating-disk of the modern watt-hour meter.

With the knowledge we possess about our transformer we are in a position to make a simple electric generator of the alternating-current type, as in Fig. 70, the primary of our transformer becoming the field coil of the generator to be connected to a storage battery. We can juggle the number of battery cells or

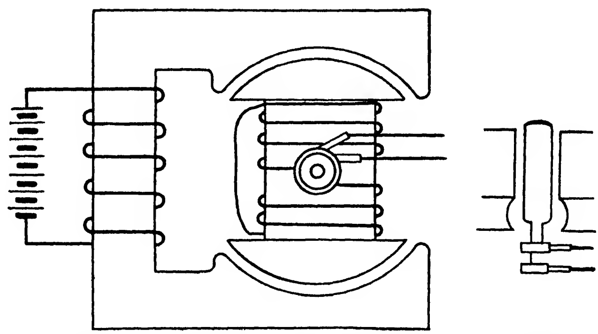


FIG. 70.—Fundamental principle of alternating-current generator and synchronous motor.

the size and number of turns of wire to give us a maximum of 265,000 maxwells through the rotor of our generator, the coil of which is the same as the secondary coil of our transformer if we want to generate 12 effective volts at 60 c per sec. by rotating the rotor at the speed 3,600 revolutions per minute. We shall, however, find it better to wind more turns on the rotor and thus require a smaller number of maxwells of magnetic flux in the iron, which will involve a smaller number of ampere-turns in the field coil. Since the directions of the electric current and magnetic flux in the field coil and iron are constant, we may use solid iron, but we must laminate the iron in the rotor.

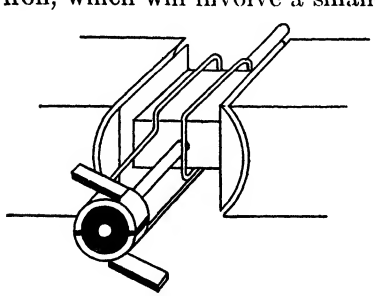


FIG. 71.—Fundamental principle of direct-current generator and motor.

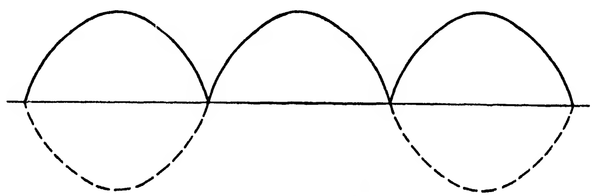
39. Direct-current Generators.—Sturgeon, the inventor of the electromagnet, was the originator of the commutator or rotary switching device found on direct-current generators and motors, that switches back every other half-wave of voltage so as to keep the current going in a constant direction in the external circuit. Thus the commutator is a rectifier when used with electric generators and an inverter

when used with electric motors, as hereinafter explained, the commutator rotating with the armature as a part thereof.

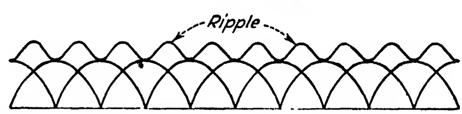
With the exception of the commutator, there is no great fundamental difference between an alternating- and a direct-current generator, since both generate alternating currents.

The application of the commutator to the alternating-current generator and its effects upon the voltage are shown in Figs. 71 and 72, respectively.

40. Electric Motors.—The early motors were of the direct-current type with commutators. The electric motor never was invented as such. It was discovered by accident. There is a



A. Rectified alternating current.



B. Effect of using four-pole armature and two field poles. The ripple results from adding the heights of the rectified waves. By winding many coils on a round armature and using many commutator bars, the ripple approaches a straight line

FIG. 72.—Rectifying alternating currents to pulsating and rippling direct currents. Compare with Figs. 115 and 127.

large book in German showing the many unsuccessful attempts to produce an efficient electric motor. At an exposition in Vienna, some direct-current generators, or dynamos, were employed for operating Jacobi candles—arc lamps consisting of two vertical carbon rods placed side by side. Something went wrong so that a "dead" generator became connected to a "live" one. Thus the electric motor was discovered. There is no fundamental difference between an electric generator and an electric motor.

A synchronous alternating-current motor differs from an alternating-current generator only in details of design. Once started, the synchronous motor keeps time with the generator in that each current wave sent out from the generator pulls the poles of the rotor of the motor to its respective field poles.

Then the direction of the line current is reversed and the rotor's poles are repelled away on the other side of the field poles. The rotor of a synchronous motor has to keep its dates at the respective field poles with the current waves sent out by the generator. That is what synchronism, unison, and so forth, mean—getting along harmoniously by keeping dates on the dot.

The rotor of the direct-current motor automatically is synchronized with its respective field-poles because its commutator or inverter changes the direct current into alternating current, that is, the direction of the current automatically is reversed at just the right instant when the peak of the reactive voltage of the rotor is numerically equal, but of opposite direction, to the line voltage. In both the direct-current generator and motor the switching is done when the current strength substantially is equal to zero.

41. Capacitance and Alternating Currents.—When an electric condenser is charged by impressing a constant unidirectional voltage across its terminals there is a rush of current as the counter-voltage due to the strained dielectric of the condenser increases from zero. When the counter-voltage of the condenser balances the impressed voltage, however, the current strength has fallen to zero. Practically, this takes place very quickly, the current falling away with time as in Fig. 61.

When an alternating voltage is impressed across the terminals of a condenser, there also is a rush of current as the condenser first is being charged, but the charging voltage then falls off, permitting the condenser to start discharging, and then the condenser is charged in the opposite direction. As a result, the current strength always is greatest when the voltage is smallest, that is, zero, and *vice versa*, because of the rush of current when the condenser first is being charged and discharged. Hence the current is said to lead the voltage by 90 deg (Fig. 73).

42. Resonance.—It follows that the reactive voltage of the condenser may be made to balance that of a reactor when properly adjusted to each other. When this is done, the reactor discharges its energy into the condenser, and when the current changes in direction the condenser discharges its energy into the reactor, thus leaving the line voltage free to do its work and to overcome resistance with the current in step or in phase with the voltage. This condition is known as resonance and is the condition whereby a reactor and condenser combination toss their energy to and fro

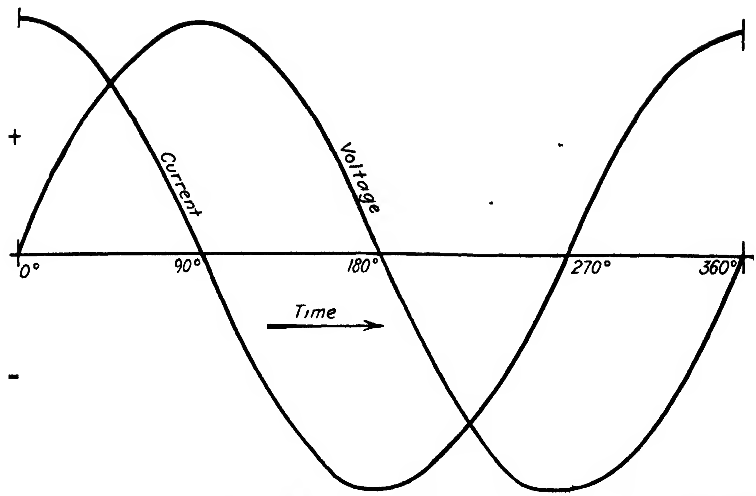


Fig. 73.—In an alternating-current circuit containing only capacitance (by assumption) the current strength is 90 deg. "early," that is, it leads the voltage by 90 deg.

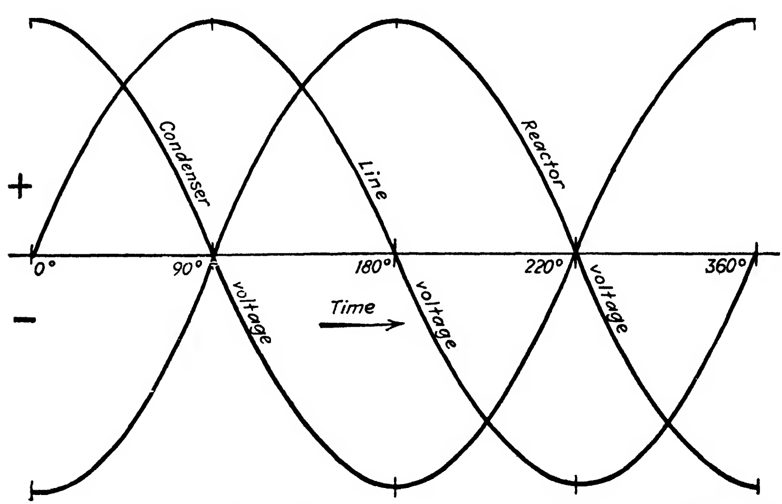


Fig. 74.—Conditions for resonance. The "line" voltage may be that of an antenna circuit; the condenser voltage that of a radio condenser, and the reactor voltage that of a radio inductance coil. When a radio receiver is tuned, resonance occurs.

at a natural frequency, as in radio apparatus, only at the line frequency in this particular case.

Radio receiving sets are tuned so that the self-inductance and capacitance of their tuning devices shall be such that the natural frequency of the radio circuit shall be the same as the frequency of the incoming waves that set up voltages in the radio's antenna. Harmony is the secret of success in the radio receiver, as well as in power reception through electric motors.

If the frequency is to be changed, adjustments must be made in either the value of the self-inductance or that of the capacitance, the latter usually being changed in radio receivers. The current strength always is greatest at resonance because of the balancing and, therefore, the elimination of the current-limiting reactive voltages besides that of resistance which, however, is not eliminated or otherwise affected, except that it produces a greater "voltage drop" across it due entirely to the greater current strength. The conditions for resonance are shown in Fig. 74.

CHAPTER VIII

SPACE, TIME, AND OSCILLATIONS

The concept of *space* offers no great obstacle to our minds, except that it is difficult to conceive its ultimate extent. If it ends at all, what is beyond the imaginary point where it ends? Einstein is reported to have abandoned the idea that all space is curved because of astronomical evidence to the contrary. We have measuring sticks for measuring space in all its three dimensions, measured one at a time, as in a room. We take a measuring stick and see how many times it goes into the distance we wish to measure.

Time is not quite so tangible. True we have clocks and watches to record its passage, but what is time? It is defined as the measure of duration or the measure of events. We think of time as a stream forever going onward. We look "backward" on "past" events, as something we passed while traveling forward with time. Time always is involved in motion. Space and time are associated with the infinite.

In dealing with *oscillations* we need to think only of length, mass and time. Shapes of things are destroyed without in the least affecting their masses. We shall digress a little at the beginning of this chapter just to bring out a few points regarding length, mass, and time, in relation to our daily lives.

43. Tick-tock.—Time flies. The pendulum swings through space across the stream of time, dividing it into sections or intervals. The clocks mark time as they tick. They are synchronized more or less accurately with the time interval required for the earth—our master timepiece—to complete one cycle or revolution on its axis in space.

Round and round goes the earth and round and round go the hands of the clocks as their pendulums or their balance wheels swing to and fro. Astronomers keep their astronomical clocks synchronized with the earth's rotation[1] and send out the correct time by radio and by wire that all may note how much their

[1] Actually, by observations of fixed stars.

clocks and watches vary, or to set them anew, for the clocks govern our lives. Appointments must be kept. We must move through a given space during a given time interval in order to keep them. People must synchronize their movements with those of others in the gigantic dance of the hours to the music of the stars. Our actions largely are governed by machines.

The huge generators at the central stations whir. Round and round go their copper-wound rotors, connected to turbines driven by expanding steam or by falling water. As the rotor of a generator revolves the electrons in the conductors move to and fro. Thus a time-keeping alternating electric current—an electric tick-tock—is generated.

The electric generators at the generating stations must keep accurate time because they may be connected with other generators on the same or other systems to help carry their loads at any instant. They must keep their appointments without previous notice. They must march right along in step with their comrades so as to take the extra loads without any hitch or delay of any kind, and they also must keep the correct time for which the synchronous motors driving various machines are designed to rotate. All must run at the same speed or frequency—keep the correct time.

So the turbines that drive the electric generators are regulated by clocks that are astronomically correct. The huge generators are in tune with the universe. That is why electric clocks plugged into light sockets keep such uncanny time. These same kinds of clocks are placed alongside the astronomical clocks in the generating stations and made to keep time with them by regulating the turbines that drive the generators that run the synchronous motors in the electric clocks. That is one way to regulate a clock.

All oscillating or to-and-fro motions have their analogues in the swinging pendulum or the balance wheel and hairspring of a clock or watch.

Radio-frequency oscillations constitute a time-keeping system or time divider wherein the time intervals are of extremely brief duration. A part of the energy of the oscillating electric currents of the radio broadcasting station is radiated into space in the form of electromagnetic waves of the same nature of light to which the radio receivers fully respond only when they are tuned to the same oscillation frequencies, or the same wave lengths,

so that the oscillating currents within them shall keep accurate time with those of the broadcasting station.

And through radio, or otherwise, one hears beautiful harmonies, from philharmonic orchestras and great electromagnetically controlled organs, or simpler melodies that keep time with the human heart—all due to the to-and-fro vibrations of various frequencies. From the remote savage to the highest form of civilization, the beat of the drum has had its psychological effects—from the slow beats of the funeral march, through the heart-quickening beats of the military band, to the rapid beats of the drums of the mad dance, as they mark off time in various recurring intervals.

Then there are symphonies in color, broadcast from the very atoms themselves, that also produce psychological effects through the intermediary of the optic nerve—all due to the motions of electrons within the atoms.

Nothing could exist without these motions, the measuring beats of time. The wave length is the space traversed between beats, like the distance between crests of the waves of the sea.

In the final analysis, nothing is supposed to exist but space and time, which are so closely bound up together that the idea of their ever being separated from each other is one of the world's greatest illusions.

Waves are visualized in consciousness as things having undulatory motions, things that keep time. But is a wave a material thing? A wave travels along a rope when one end of it is shaken. That wave was a traveling *shape* of the rope. What became of the wave and its shape after it had passed? A wave is not a rope; neither is a wave water or air. A wave is no more tangible than its shape, frequency, speed, or energy.

44. Pointers, Scales, Ratios, and Symbols.—Pointers control our actions and those of machines. The hands of our clocks and watches point out the nearest hours, minutes and seconds. We have measuring scales to indicate distance; weighing scales to indicate forces; speedometers indicate velocity—the ratio of length to time; ammeters indicate how many coulombs of electricity are passing a given mark on a conductor every second; voltmeters indicate the magnitude of difference of potential—the work done per coulomb of electricity moved past a point; ohmmeters indicate the ratio of the difference of potential to the heating electric current strength. Then there are ther-

mometers; watt-hour meters; hydrometers, and so on—all to measure, indicate, and record in terms of our arbitrary standards the quantities recognized in our experience and common-sense outlook, as has been well described by Eddington.

Through the ratios and other mathematical relationships between length, mass, and time are derived all other physical quantities, as velocity, momentum, energy, and force, to which are assigned unit values and arbitrary symbols. Hence our world is a world of symbols. We can weigh a body; divide the weight (gravitational force) thus determined by the known acceleration due to gravity (a gain of 981 cm or 32.2 ft. per sec., every second) to obtain the magnitude of the mass of the body; write, for example, $M = 60$ g, and then forget all about the actual body whose mass experimentally was determined since only a *property* of the body—mass in this case—is required for further computation.

45. Analogues.—Only the mathematical physicist adequately and correctly can describe in terms of probability the various phenomena associated with individual electrons because no one knows just how an electron will react to a given disturbance. The older physics and engineering, however, are based on *average* behaviors; hence, when we deal with large numbers of electrons and atoms, we can compute with great accuracy what these large numbers of electrons and atoms will do, although we may know nothing about what any individual atom or electron may be doing or how it will react to the force which we expect to apply to all of them; but we can estimate with at least the accuracy of our most sensitive instruments just what will happen to the whole lot. Therefore, in engineering we are not concerned with wave mechanics[1] and probability, except in certain cases which are discussed in Chap. XXVI.

The world is filled with illusions, largely because of apparent similarities and occasional coincidences, and we shall endeavor to give these a wide berth. In engineering, however, it is perfectly proper to refer to difference of potential or voltage as electric pressure, and magnetic flux as electromagnetic momentum, because difference of potential or voltage *acts* like a pressure and magnetic flux *acts* like momentum—mass $\times$ velocity. All mass is supposed to be electromagnetic in character,

[1] Which supposes that electrons and protons possess many of the properties of waves.

due entirely to moving electric charges—the greater the velocity the greater the mass.

46. Observations.—Electrons possess mass, and the mass of each electron at various speeds accurately is known. A very large number of free electrons constitutes a quantity of negative electricity.

When an electromagnet or a reactor is connected in a direct-current circuit, as by closing a switch, the current strength and, therefore, the velocity of the electricity, tend to increase at a constant time rate, showing that the electricity possesses the property of inertia, that is, the electrons composing it possess mass due to the magnetic flux associated with them at a given velocity; they are accelerated, going faster and faster as time elapses. Since the mass usually is relatively small, the time interval required for them to approach their maximum velocity when electric resistance is present (when the voltage is exerted exclusively in converting the energy of the circuit into heat in the conductor, at the maximum current velocity or strength) is correspondingly small.

When there is little or no electric resistance present, as when metal conductor temperatures approach the absolute zero of temperature, the electric current tends to flow on "forever" on its own momentum, after having been set in motion through electromagnetic induction. The action is as though the electrons forced open something ahead of them in space and that said "something" collapsed back of them, thus keeping them going without loss of energy due to that "something." An analogue is found in the aorta—the large artery leading from the heart. The aorta elastically widens with each expanding pulse and elastically collapses behind it.

When an attempt is made to arrest the motion of an electric current, as when a switch is opened, the action increases the driving voltage and the electricity tends to keep right on going, jumping across switch contacts and producing a spark or arc between them, just as a moving body of matter shows "fight" when opposed.

Electrons are just as real as matter itself, but no one knows what reality is. Planck has stated, however, that in physics "whatever can be measured is real." We can measure the phenomena associated with gross matter and also with enormous numbers of electrons, and we believe that their underlying laws

are very similar, if not identical—not for individuals, but for mobs.

There is nothing more mysterious about electric potential and current strength than there is in the pull of gravity and water flowing downhill. Both are well understood from our common-sense outlook. What is mysterious and uncertain is the number of free electrons in a solid metal conductor and their average velocity in an electric current therein. Physicists now are struggling with the mechanism of electric conduction in metals.

47. Effects of Inertia, Elasticity, and Friction.—From a very general viewpoint, there are three major properties of things to be considered, all of which are associated with energy.

The first property is that which causes anything to resist, or tend to resist, being set in motion and, once in motion, to resist, or tend to resist, being retarded or deflected. This property is inertia due to mass.

A baseball resists being thrown. Therefore a pitcher must exert much force in moving it through a distance before releasing it in order to speed up, or accelerate, its motion to the required speed or velocity. The energy expended by the pitcher exclusively in setting the ball in motion is equal to the product of the average force exerted by him and the distance the ball moves before he releases it, that is, work = force × distance.

The ball travels on its own momentum (mass × velocity), carrying with it the energy expended by the pitcher, now kinetic energy (half the mass × the square of the velocity).

When the catcher stops the ball he does not do so instantly, for the force of impact moves his hand somewhat, thereby permitting the energy carried by the ball to be expended over a distance. The smaller the distance in which a body is stopped, the greater is the force (counter-force) required to stop it. Force = energy ÷ distance. Force is defined as the time rate of change in momentum. It is evident that the more rapidly the motion of a body is accelerated or retarded, the greater will be the force in either case.

The above is substantially what happens in an electric circuit containing only self-inductance when the electric current is substituted for the ball and voltage is substituted for force. Magnetic energy = half the self-inductance × the square of the current strength, which should be compared with the above definition of kinetic energy.

The second property is that which resists, and continues to resist, the displacement of anything from its natural or mean position. This property may be called elasticity. Examples are gravity, springs, live rubber, and compressed air. The dielectric or insulating material of an electric condenser is an electrically elastic material. Potential energy is stored when a body is lifted, a spring is extended or compressed, and so forth.

The third property is that which offers some resistance to all motion by converting some of the kinetic energy into heat. This property is friction. Friction and electric resistance, respectively, tend to slow down or "damp out" the motions of matter and electricity. Electric resistance sometimes is called electric friction by analogy. The energy converted into heat in solids is changed into kinetic energy therein.

To appreciate the effects of inertia, try moving the hand to and fro as rapidly as possible. It will be observed that much more effort is required to move the hand at a constant to-and-fro frequency through, for example, a foot each way than through only a few inches. One's hand possesses mass. Force is required quickly to set it in motion, as toward the right, and force then must be exerted toward the left to stop it and then set it in motion toward the left, and so on, just as in the case of the line voltage trying to keep the free electricity in a conductor alternating to and fro (Art. 35). That is why self-inductance is called the electromagnetic inertia of a circuit.

Next hold an average-sized book in the hand and repeat the experiment. Note how much more slowly the hand and the book move together. The force exerted is about the same as before, but the mass moved is greater, so the number of to-and-fro motions per minute or per second is reduced accordingly.

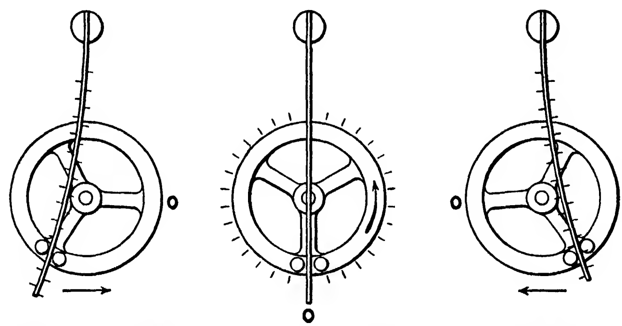
If the hand alone, or the book in the hand, is pressed against a table top while being moved to and fro, the to-and-fro distance of movement will be reduced, for the same frequency of movement, due to friction.

These three things are all we have to consider in connection with the energy, forces and motions of matter and electricity *in bulk*.

48. Oscillating Systems.—The wheel-and-spring illustration in Fig. 75 is an exact analogue of the balance wheel and hairspring of a clock or watch; of a pendulum, and of a single-turn inductance coil (or reactor) and electric condenser in combination. The

radial lines indicate where the energy is and the arrows show the directions of the forces and motions. At intermediate positions, there always is some kinetic energy in the wheel and some potential energy in the spring.

Referring to Fig. 75*A*, when the wheel is moved forcibly to the position shown, potential energy is stored in the spring, thereby producing a force tending to move it and the wheel in the direction of the arrow. After the spring has accelerated the wheel and assumed its normal or mean position (Fig. 75*B*), its potential energy has been completely expended and it exerts no force whatever in either direction. Then the energy (that has not been converted into heat through friction or dissipated through



A. Energy (potential) all in the spring Maximum force on spring. No motion.

B. Energy (kinetic) all in wheel. No force on spring. Maximum velocity.

C. Energy (potential) all in spring. Maximum force on spring. No motion.

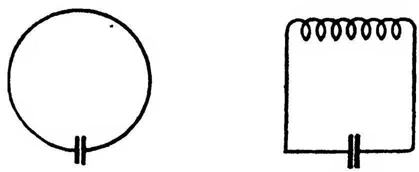
FIG. 75.—Principle of harmonic motion and oscillations.

air resistance, and so forth) has been stored in the wheel in the form of kinetic energy. As the wheel continues to move in the direction of the arrow it tends to move the spring in that direction, thereby expending some of its kinetic energy and storing it in the spring in the form of potential energy; but the spring immediately resists as the energy is stored and exerts a counter-force until the motion of the wheel is completely arrested (Fig. 75*C*). Then the same procedure takes place in the opposite direction until the cycle is completed, when the conditions again are as in Fig. 75*A*, except that the wheel will not swing clear back to its original position due to some loss of energy during the cycle.

Referring to Fig. 76, coiling an electric conductor increases its electromagnetic inertia (self-inductance), as already described.

In the symbolic representation of an electric condenser the parallel vertical lines represent the metallic plates while the elastic part of the condenser—the vacuum, air, paper, or other dielectrics between the plates—is left to the imagination.

Figure 77 is an exact analogue of Fig. 75. The dashes between the plates of the condenser indicate that the medium between them is strained. The curved lines indicate the magnetic



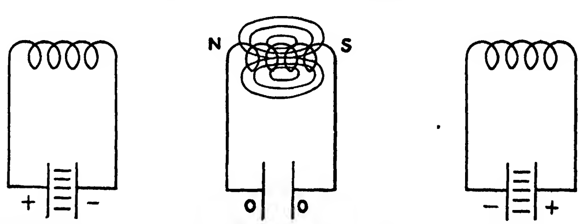
A. Single-turn inductance coil or reactor and electric condenser.

B. Many-turn inductance coil or reactor and electric condenser.

FIG. 76.—Electromagnetic oscillators.

flux interlinked with the moving electrons in the turns of the inductance coil or reactor.

If a frictionally mounted pendulum with sand running from its bob is pulled to one side and then released while a sheet of paper is moved beneath it at a uniform velocity to represent the stream of time, the sand will leave the track depicted in Fig. 78, which also represents the force-time characteristics of the wheel-and-



A. Energy all in condenser. Maximum voltage. No current.

B. Energy all in reactor. No voltage. Maximum current strength.

C. Energy all in condenser. Maximum voltage. No current.

FIG. 77.—Principle of electrical oscillations.

spring combination in Fig. 75 and those of the reactor-and-condenser combination in Fig. 77.

An oscillating current is nothing but electricity in motion as it swings to and fro in the circuit. The greater the surface of the electrically elastic medium of the condenser, the greater is the quantity of electricity that can be displaced between the plates for a given difference of potential between them. Only a certain amount of electricity per volt can be displaced per square inch of

surface of dielectric. Doubling the number of square inches of dielectric doubles the quantity of electricity displaced by the same voltage, for voltage is a pressure. A dielectric sheet of uniform thickness is meant in the foregoing.

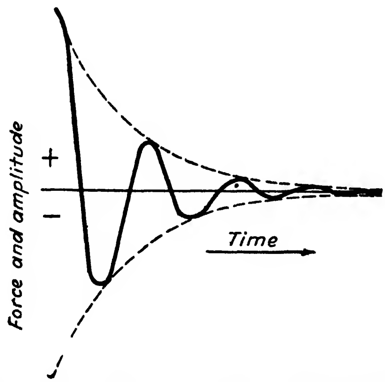


FIG. 78.—Damped-oscillation characteristics.

The velocity-time characteristics corresponding to the force-time characteristics in Fig. 78 are shown in Fig. 79, the major difference being that the velocity is maximum when the force is

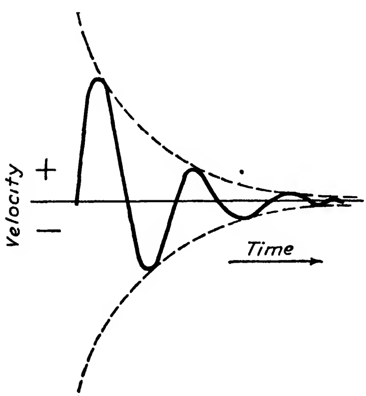


FIG. 79.

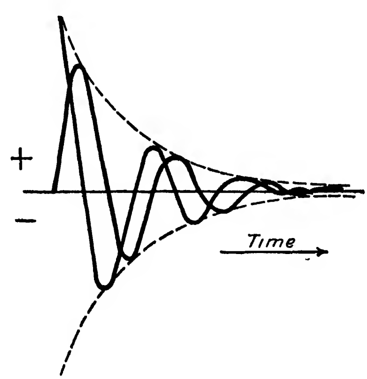


FIG. 80.

FIG. 79.—Velocity characteristics of damped oscillations.
FIG. 80.—Combined characteristics.

zero, and *vice versa*. The two curves are shown to the same scale in Fig. 80.

49. Sustained Oscillations.—All oscillations tend to be damped out by friction and their energy converted into heat. The only

reason one winds a clock or a watch is to store up a supply of potential energy that will be converted into heat through friction and air resistance over a period of a day or a week.

Oscillations in mechanical clocks and watches are sustained through escapements, whereby a "kick" is given the pendulum or balance wheel during each half-cycle to compensate for the loss of energy therefrom during that half-cycle.

When a radio receiver is in tune with the sustained waves from a broadcasting station the energy of each half-wave provides the "kick," by way of the antenna, necessary to start and sustain the natural oscillating current in the radio receiver (Fig. 81). When such "kicks" come from out-of-tune waves, interference results. Furthermore, if the radio receiver is not tuned to the frequency of the incoming waves, the kicks may tend to stop oscillations as much as they tend to start them, or at least to prevent the free motion of the electrons in the oscillating system.

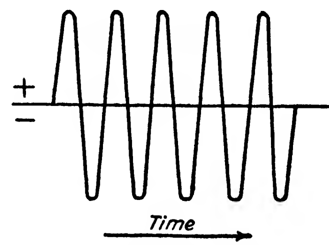


Fig. 81.—Sustained oscillations.

Tuning also is advantageous in industrial plants employing underloaded induction motors because these motors require two currents which are combined in the total current, namely, the magnetizing current and the motor-running current. Normally, the magnetizing current must be supplied from the generating station. This extra current heats transmission lines, feeders, and industrial-plant distribution systems, entailing losses and poor voltage and speed regulation unless remedied. One way of overcoming this difficulty is to connect electric condensers (also called static condensers, capacitors, permittors, and so forth) across the terminals of the induction motors. Then, as the magnetizing energy is exhausted from the motor (exactly as from an inductance coil or reactor) during every other half-cycle, it is stored in the condenser, from which it is discharged again during the following half-cycle to again magnetize the motor, thus reducing the total current to substantially the necessary running current by keeping most of the magnetizing current out of all wires, except those between the motors and the individual condensers. Large numbers of installations have proven that tuning in industrial plants is as necessary as in the radio.

CHAPTER IX

ELECTRONIC TUBES

What is space? There is a wide diversity of opinion about it, especially since the Michelson-Morley experiment which showed that the earth, in moving through space, does not drag the ether along with it, as it apparently should if the ether was present. Hence some think the ether does not exist. No one, however, seems to think of space as void—nothing. While some physicists object to the term ether, they still conceive of "something" in the vacuum, which mathematicians represent by mathematical symbols. Since this "something" heretofore has been thought of as the ether, the term is retained in this volume. When we place two electrodes in a vacuum tube we make an electric condenser with vacuum between its plates. We plan to shoot electrons across the space through the ether from one plate to the other. The trick is to get the electrons out of one of the metal electrodes. Thereafter, they travel freely enough through the ether, and a number of things happen wherever they strike. Some of these phenomena are described in the present chapter.

50. We Live in a Vacuum.—All of the heavenly bodies, including the earth upon which we dwell, are isolated from each other by space—vacuum or the ether. All light, heat, and cosmic rays, as well as enormous numbers of electrons, pass through this vacuum in reaching our planet and, since the earth possesses a negative electric charge, it is, in some respects, like an electrode in a vast vacuum tube. Above and at the earth's surface, air molecules dart hither and thither at a speed of about ¼ mi. per sec., but through minute distances, thus hammering against our bodies with a pressure of about 15 lb. per sq. in.

The upper atmospheric layer, called the Kennelly-Heaviside layer, is ionized through the constant bombardment of electrons from space, thus reflecting radio waves and causing fading. Appleton and Builder sent out intermittent radio pulses which were photographically recorded on a high-speed oscillograph three miles away. By comparing the direct and reflected impulses, the

latter were shown to have traveled 70 mi. upward and back again. Cohn reproduced the sky's blue by bombarding ions with electrons and it is believed that electrons from space bombarding the ions of the Kennelly-Heaviside layer are at least partially responsible for the sky's blue.

When the physicist examines atoms, he finds them almost entirely empty, the electric charges of which they are composed being extremely far apart relative to their dimensions—if they have any dimensions besides wave-length and amplitude. Hence what we call solid matter consists of swarms of electric charges that hold us up by pounding upon the soles of our feet.

51. Vacuum Condensers.—An electric condenser with a dielectric material between its plates is comparable to a sort of electrolytic cell wherein the electrons and positive ions can be but slightly displaced from their average positions with relatively low voltages. If the dielectric is air, however, and the difference of potential is great enough to cause it to be ionized, electric currents may move between the plates. It is impossible by present means of evacuation to get all of the air molecules out of any kind of a sealed tube. Jaycox and Weinhart measured a vacuum containing only one three-trillionth of the original amount of air, by an ionizing method. Even then there remained 500 million air molecules in every cubic inch of space within the tube. Hence in speaking of vacuum tubes, those wherein only an exceedingly small percentage of air remains generally are meant, those having a high degree of vacuum being termed "hard" tubes and those with lower degrees of vacuum being termed "soft" tubes, while those which purposely are filled with gas are called gas-filled tubes or gaseous-discharge tubes.

In a broad sense, a simple two-electrode vacuum tube is an electric condenser to the extent that, in operation, each electrode must possess a charge; a potential; some capacitance, and there is a stress in the ether between them which is proportional to the difference of potential between them. Even though the electrodes may be rather widely separated, the operation of the device depends upon all of these phenomena. The capacitance of a vacuum tube leads to "squeals" due to local oscillations in radio receivers unless prevented, as is done by a number of methods.

Consider such an electric condenser, with plates rather far apart, in vacuo—otherwise a two-electrode vacuum tube (Fig. 82). There is nothing but the best obtainable vacuum between

the electrodes. Vacuum is an electric insulator. Vacuum is also an electric conductor. Thus a portion of a vacuum may be an insulator, while another portion may be an electric conductor. Vacuum is an electric insulator when there are no free electrons or ions in it, a conductor when electrons or ions move through it.

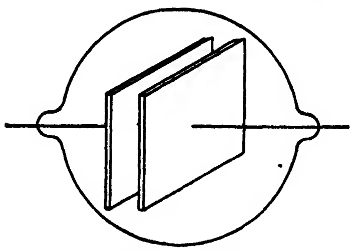


Fig. 82.—Electric condenser in vacuo.

Electrons tend to remain with the positive ions in cold metals, and a strong negative potential is required to drive them out. When the difference of potential between the plates of a vacuum condenser, that is, between the electrodes of such a vacuum tube, is not great enough to drive them out, they merely are displaced slightly from the normal "habitat" in the cathode and toward the anode, thus charging the vacuum condenser. But if the difference of potential is sufficiently great, electrons will be expelled from the cathode and attracted to the anode, moving at ever increasing exceedingly great speeds until they strike the anode much as bullets strike a target.

Just what happens when an individual electron strikes an individual atom in the anode is a matter of chance. It may produce an x-ray; it may knock out a secondary electron, or it may merely heat it, that is, its energy of impact may be converted into kinetic energy in the atom. But when the enormous numbers of electrons employed in such tubes are shot across at the plate, all three phenomena simultaneously occur. It is all a matter of getting electrons out of metals—something like breaking down the dielectric of a condenser by setting electrons speeding away from the positive ions.

The electrons are propelled from the cathode to the anode in the electric field, in the ether between them, whose strength is the ratio of the difference of potential to the distance between the electrodes, expressed in terms of volts per centimeter. The rule for finding the electronic speeds is given in Art. 162.

52. Geissler Tubes.—Numerous early investigators studied electric discharges through gases in sealed glass bulbs under varying degrees of vacuum. Quet, for example, found that if vapors of turpentine, alcohol, and so forth, were placed in the bulb before exhaustion, the discharge therein appeared as a series of

bright and dark zones. These phenomena first were investigated by Gassiot in Geissler tubes (Fig. 83).

De la Rue and Muller made a very extensive series of experiments, using a battery of 11,000 volts. Narrow streaks, streamers, stripes, or bands of distinctive color, called striae or striations, start from the anode, a single striation falling down a tube, like a feather in a vacuum, due to diminishing the pressure of the gas. Under given conditions the striations were found to be very permanent. A change in the current strength or the pressure of the gas often produces an entire change in the color of the striations. The color for air varies from carmine through salmon to pale white, with decreasing pressures. While no discharge could be obtained with that voltage with high exhaus-

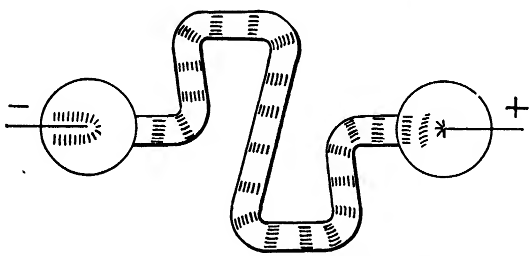


Fig. 83.—One form of Geissler tube.

tion, when a small amount of caustic potash, placed in the tube under certain conditions, was heated the discharge occurred.

Plucker found that the light in a Geissler tube depended only on the nature of the gas therein, and that the colored lights given by hydrogen, nitrogen, and so forth, gave different spectra (Art. 121) when they were decomposed by a prism.

With only one kind of gas in the tube, the color of the light emitted depends upon that gas, being a brilliant orange-red with neon, yellow with helium, red with hydrogen, brick-red with nitrogen, and greenish with mercury vapor.

As the pressure is reduced in a gas-filled tube while the voltage is applied to the tube a wavy streamer or striation of light eventually passes from one electrode to the other. As the pressure further is reduced, the streamer broadens. As the pressure of the gas is reduced, therefore, it increasingly becomes conductive until a maximum is obtained, when the conductivity decreases until it again becomes an extremely poor conductor at very low pressures.

During the Geissler discharge, the glow at the cathode is separated therefrom by a narrow dark space, the light intensity also being weaker on the far side of the glow. Figure 84 shows about how the slow discharge is divided in appearance, wherein *A* is the cathode layer, *B* is the dark cathode space, *C* is the negative glow, *D* is the intermediate dark space, and *E* is the positive column which may contain striations, the actual appearance being quite different. These light effects are utilized in

Fig. 84.—Bright and dark zones of the Geissler discharge. The shaded portions herein represent light.

electronic lamps. The luminous spaces, *A*, *C*, and *E*, are those wherein ionization is taking place. The spaces between are those wherein the electrons and positive ions move freely.

53. Cathode Rays.—Some transparent bodies possess the property of giving off, when illuminated, light of a color differing from their own and from that of the light illuminating them, that is, that of the incident light. This effect, called fluorescence, is very brilliant in the glass of a Geissler tube when the electric discharge occurs. Plucker found (1858) that the fluorescence was due to rays from the cathode. Crookes described them in

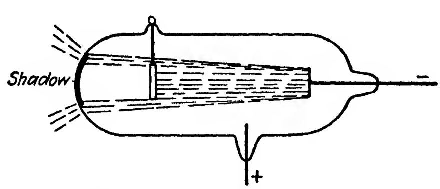


Fig. 85.—Cathode rays produce fluorescence and phosphorescence where they strike the glass. Objects placed in their path cast shadows.

1879 under the name of "radiant matter," as he then thought them to be atoms, and showed that they proceed in straight lines from the cathode at right angles to its surface; that they cause glass, but particularly jewels, to shine in the dark after exposure to the rays (phosphorescence); that an obstacle, whether opaque or transparent, placed in their way casts a sharp shadow (Fig. 85); that they exert a mechanical pressure where they strike; that they can be deflected by a magnet (Fig. 86), and that they also pro-

duce intense heating effects, even melting platinum foil in their path (Fig. 87).

Between the years 1875 and 1898, there was much dispute as to the nature of cathode rays, some believing them to be negatively charged particles shot off with great speed from the surface of the cathode, while others thought they were waves in the ether, some sort of invisible light.

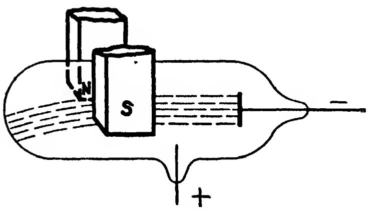


FIG. 86.

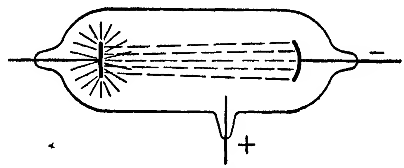


FIG. 87.

FIG. 86.—Principle of deflection of cathode rays by a magnet.
FIG. 87.—Cathode rays concentrated on platinum foil produce so much heat through bombardment as to melt it.

Cathode rays would not pass through glass, mica, or any substance through which ordinary light will penetrate, with the voltages then employed, but Hertz discovered that they will pass through metal foil. By placing a piece of aluminum foil (called the Lenard window) covering a hole less than 2 mm in diameter, at one end of a cathode-ray tube exhausted to about a millionth of an atmosphere, Lenard (1894) succeeded in projecting cathode rays therethrough and into the surrounding air, where they still retained their property of producing phosphorescence, causing

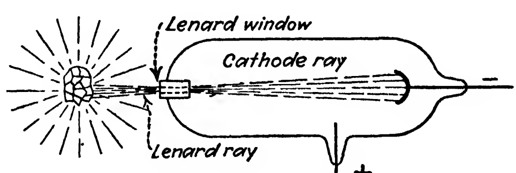


FIG. 88.—Producing Lenard ray.

minerals to glow and to continue to glow sometime after the rays had been discontinued. Hence, cathode rays passed through the window outside of the tube are called Lenard rays (Fig. 88). These rays are useful for ionizing gases, thus making them conducting.

Uncharged molecules or atoms of the cathode material also are torn off and deposited on the inner wall of the tube. This

phenomenon is termed sputtering. It has a pronounced effect upon the life of an electronic tube.

In 1895, J. J. Thomson proved that the cathode rays were deflected by negative charges (Fig. 89), and later, Perrin proved that they impart charges to bodies upon which they impinge.

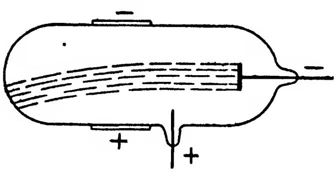


Fig. 89.—Principle of deflection of cathode rays by electric charges.

In a series of experiments, J. J. Thomson found that the cathode ray consists of negatively charged "corpuscles," the mass of each of which was less than a thousandth of that of the hydrogen atom, in other words, cathode rays are streams of electrons. Thomson determined the charge and the mass of the electron, and later Millikan made more exact determinations.

Thus the electron, which first was detected in the dilute solution, came to be definitely identified and measured. It is remarkable how closely Stoney determined the charge of the electron from Faraday's discovery and the kinetic theory of gases (Art. 11).

Since the rapid stream of electrons in a cathode-ray tube can be deflected by a magnetic and also by an electrostatic field, transient and high-frequency currents can be studied by causing their fields to deflect the electrons in proportion to their strengths and directions, thus causing them to trace out a fluorescent path on a screen at the end of the tube where they strike in the cathode-ray oscillograph.

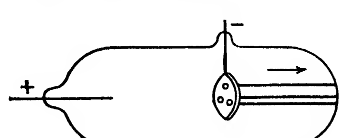


Fig. 90.—Principle of production of positive (canal) rays.

54. Positive Rays.—When a disk cathode is perforated with small holes (Fig. 90), "canal rays" pass in pale blue lines through the openings. They are deflected slightly in very strong magnetic fields in such a manner as to show that they are positively charged and have a mass at least a thousand times that of an electron, while their speed is at least a thousand times less than that of electrons. They also produce a different kind of phosphorescence than do electrons. They are now known to be positive ions. The positive ions readily lose their charge as they move through gas, wherefore they are studied in vacuo by photographic and other means.

In 1912, J. J. Thomson discovered two kinds of positive rays. Aston made a very complete investigation of both kinds of rays with special tubes, using various materials for the cathode, and found that not all of the atoms of the various substances possess equal masses in the same substance. They are known as isotopes. They show that the usual atomic weights simply are the average of the atomic weights of the isotopes.

55. The Edison Effect.—Edison discovered that an electric current flowed between the "heels" of the filaments of the incandescent lamps of his invention (Fig. 91), which phenomenon is given the above name. In 1883, he built some bulbs with plates alongside the filaments in as good a vacuum as he could obtain and measured the strengths of the currents which flowed in these pioneer rectifiers. In 1884, he made several lamps of different forms and characters, with the plates in various positions, for Preece to enable him to investigate the phenomenon more carefully in England. In consequence, the first radio vacuum tubes came from that country.

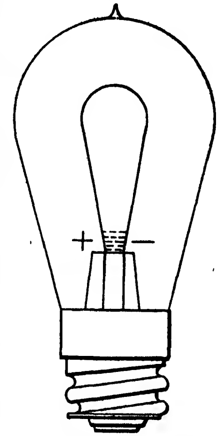


FIG. 91.—Discovery of the Edison effect.

In 1889, Fleming referred to the foregoing and stated:

> If a platinum wire is sealed through the glass bulb of an ordinary carbon filament lamp and carries at its extreme end a metal plate, so placed as to stand up between the legs of the horseshoe without touching them . . . when the lamp is actuated by an *alternating* current a *continuous* current is found flowing through a galvanometer, connected between the insulated plate and either terminal of the lamp. The direction of the current through the galvanometer is such as to show that negative electricity is flowing from the plate through the galvanometer to the lamp terminal.

This is illustrated in Fig. 92. A galvanometer is a very sensitive electromagnetic indicating instrument. A simple form is a coil surrounding a compass needle.

56. The Fleming Valve or Diode.—Eventually Fleming employed the Edison effect in rectifying alternating currents by connecting the heated filament and cold plate in radio-frequency receiving circuits, the filament being heated by a

current from a battery. The Fleming valve consists of what we now know as an ordinary radio tube without a grid (Fig. 93), with the plate placed outside of, and close to, the filament. It is a hot-cathode vacuum tube.

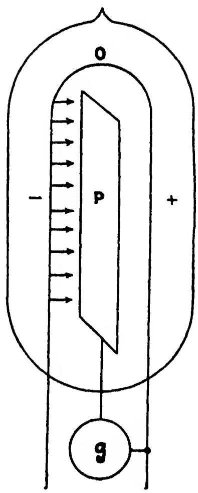


FIG. 92.—Fleming's discovery that an alternating current in the filament always produces a continuous current in the galvanometer g. *P* is the plate. The arrows show the direction of electron flow.

When the temperature of a metal becomes relatively high, electrons are boiled right out of it (Fig. 94) with such violence that they have sufficient speeds to carry them to the plate, thus forming very weak currents. Thereafter they may be driven away from the hot cathode to the cold anode with relatively small differences of potential between these electrodes, whereas relatively high voltages are required to tear electrons from the filament when it is cold. Such currents are called thermionic currents and the tubes sometimes are termed thermionic tubes.

Thus when a small alternating difference of potential is applied to the Fleming valve, electrons flow from the hot cathode or filament to the cold plate (Fig. 95), but not from the cold plate to the hot filament when the potential reverses. The electrons in the space between the cathode and anode are called the space charge.

Normally the plate remains cold. Thus the device acts as a check valve in that it will permit electron currents to pass only in one direction—from the hot filament to the plate. When the plate is excessively heated by electronic bombardment, however, as when too high voltages are used, electrons also flow from the plate to the filament when the plate potential is negative and that of the filament is positive. The tube then ceases to function in a normal manner, because electrons can flow from the filament to the plate during one half cycle and from the plate to the filament during the following alternate half cycle.

The Fleming valve first was employed as a radio detector, that is, as a half-wave rectifier, to eliminate every other half-wave of the oscillating current (Fig. 96) in the radio receiver so that the musical dot-and-dash code signals might be heard in telephone receivers, which cannot respond to the high-frequency radio currents because of their relatively high self-inductance

and the inertia of their diaphragms, and which would produce no audible sound, for the pitches of such sounds are many times above the range of the human ear.

The difference of potential between the filament and the plate commonly is called the plate potential. When this is constant, the hotter the filament becomes the greater is the thermionic emission of electrons therefrom and the stronger is the electron

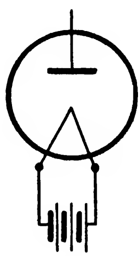


FIG. 93.

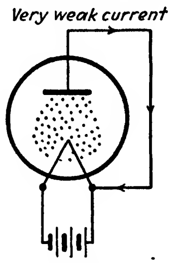


FIG. 94.

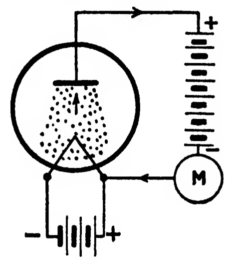


FIG. 95.

FIG. 93.—Fleming's valve or diode.

FIG. 94.—Illustrating how electrons are boiled out of a hot filament to form a thermionic current.

FIG. 95.—Illustrating the movement of the space charge in the direction of the cold plate to form a space current. *M* is a milliammeter.

current from the filament to the plate, commonly called the plate or space current, until the current strength increases no further; then it is referred to as the saturation current strength.

This is illustrated in Fig. 97, wherein curve *A* represents the (exponential) manner in which the plate current varies with filament temperature when the plate voltage is strong enough to carry all of the electrons emitted from the filament over to the plate. With smaller plate voltages, however, the saturation

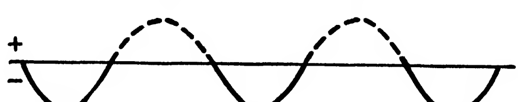


FIG. 96.—Electron current in Fleming valve as an alternating current is rectified. This is termed half-wave rectification.

current strength does not rise above certain fixed values, depending upon said voltages, as at *B* and *C*.

Although the electrons are moving very rapidly, at any instant they form a space charge between the filament and the plate. These electrons repel the electrons which are emitted from the filament when the plate voltage is low, thus limiting the ultimate plate current strength.

Figure 98 shows the relationship between the plate current strength and the plate voltage with constant filament temperature. It is seen that the plate current strength can be

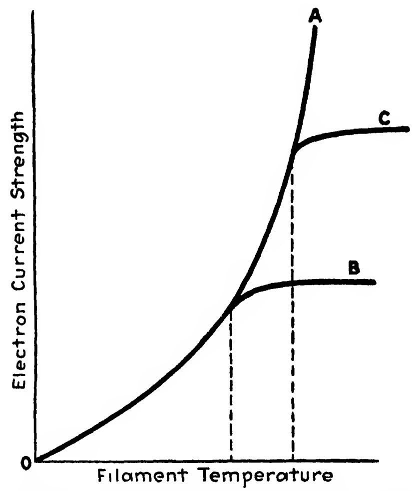


FIG. 97.—Effect on plate or space current of variation in the filament temperature and the plate voltage.

reduced to zero only by making the plate voltage slightly negative. This is due to the thermionic current in a closed circuit

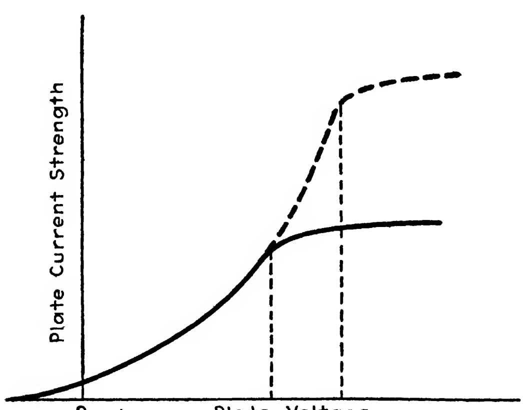


FIG. 98.—Conditions for a diode with constant filament temperature.

produced by the initial speed of the electrons as they are boiled out of the filament. The dotted curve shows the effect of increasing the filament temperature.

Thus there are three distinct current-voltage relations in a two-electrode vacuum tube of the hot-cathode type. These are the current due to the initial speed of the electrons, which usually is very small; the current which is limited by space charges; and the effect where all emitted electrons pass to the plate.

57. Triodes.—In 1908, DeForest was granted a patent for a Fleming valve (and associated circuits) with a metallic grid interposed between the filament and the plate (Fig. 99). This three-electrode tube (which he called an audion) is capable of acting as an inertialess (in the ordinary sense) relay and

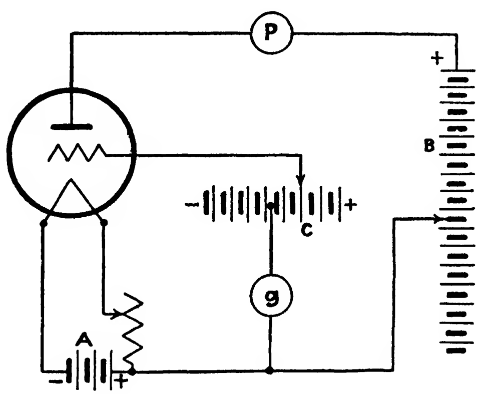


FIG. 99.—Three-electrode vacuum tube or triode and connections for varying the filament temperature, positive plate potential, and for reversing or varying the grid potential. *P* is the plate milliammeter and *g* is the grid microammeter.

amplifier by controlling currents with much weaker ones (charging currents); changing alternating currents into direct currents, as a rectifier; changing direct currents into alternating currents, as an inverter—all with the associated circuits and sources of electrical energy.

Electrons must pass through the grid to reach the plate. When a positive potential is applied to the grid (a small charging current is required to do this), it aids the plate potential in pulling the electrons from the filament to the plate, whereas a negative grid potential retards the electrons, by repelling them as the plate potential attracts them, thereby controlling the space charge. These grid potentials are more effective than are changes in the plate potential (or changes in the filament current and temperature) in changing the plate current. Thus, as great

an increase in the plate current may be obtained by increasing the grid potential (and thereby its charge) by 1 v as would be caused by an increase of, for example, 6 or 8 v in the plate potential, other conditions being constant.

The voltage amplification (symbol μ) of a tube is the ratiȯ of the change in the plate potential to the change in the grid potential required for equal changes in the plate-current strength.

Referring to Fig. 98, when the grid potential is zero in a certain tube (grid not connected) a change in the plate voltage from 45 to 90 v, an increase of 45 v in the plate potential, causes the plate current to increase from 0.7 to 2.0 ma., an increase of 1.3 ma.

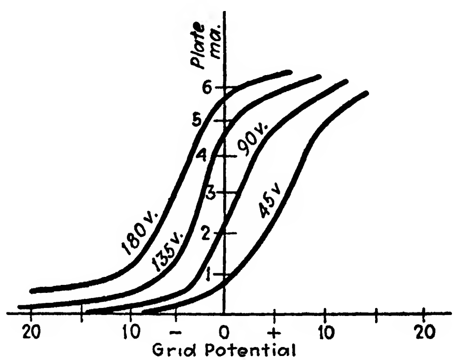


FIG. 100.—Tube (triode) characteristics obtained with the general connections in Fig. 99 with constant filament temperature.

Figure 100 shows how the plate current of the same tube changes with variations in both the plate and the grid potentials. It is observed that when the plate potential is 45 v and the positive grid potential is made 4 v, the plate current is increased from 0.7 to 2.0 ma., an increase of 1.3 ma. Hence a change of 4 v in the grid potential produces the same change in the plate current as would be obtained by changing the plate potential by 45 v; therefore, the voltage amplification is about 11 in this case.

The screening action of the grid was discussed by Maxwell in his book, "Electricity and Magnetism," Vol. I, years before its introduction into vacuum tubes.

The new catkin all-metal radio tubes with only glass seals, announced in 1933, should mark a new epoch in radio. These tubes somewhat resemble large water-cooled tubes called "cooled-anode tubes" (cats). Hence the name of the small tube.

58. Negative Resistance.—When the grid potential is made positive, there is a grid current as well as a plate current, though much weaker, that is, the electrons which strike the grid pass into it and drift back through the connecting wires toward the filament. When electrons strike the grid, they also forcibly eject secondary electrons therefrom, the phenomenon being referred to as secondary emission. The greater the positive grid potential, the greater is the time rate of ejection of secondary electrons. These modify the effective space charge.

Figure 101 illustrates how the grid current increases to a positive maximum, falls to zero, increases to a negative maximum, and falls back to zero again, as the grid potential increasingly is made positive. This is due to secondary emission, the number of electrons arriving at the grid from the filament at first greatly exceeding the number of secondary electrons ejected therefrom and attracted over to the plate; thus the grid current strength reaches a maximum value (at A) with increase in positive grid potential until secondary electrons leaving the grid cause a reduction in the grid-current strength; this reduction continues until, when secondary electrons leave the grid for the plate as rapidly as electrons arrive at the grid from the filament, the grid-current strength is zero at B.

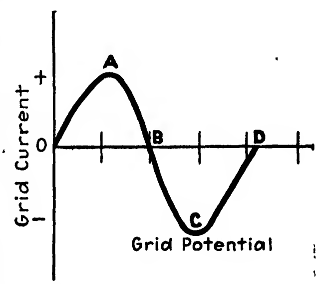


FIG. 101.—Effect on grid current of varying the grid potential with filament temperature and plate potential constant, due to secondary emission.

With increasing positive grid potential the number of electrons ejected from the grid increasingly exceeds the number of electrons which knock them out of the grid; thus the grid current becomes increasingly negative until the grid potential becomes sufficiently strong to draw the secondary electrons back to the grid (away from the plate) in increasing numbers until electrons are arriving at the grid as rapidly as they are leaving it, when the strength of the grid current again is zero at D.

Thus an increase in the positive grid voltage causes a decrease in the grid current between A and C, that is, it keeps getting more and more negative between these points, where the tube is said to have a negative resistance, as in arcs (Art. 99), which makes it possible to obtain electrical oscillations or "squeals"

in three-electrode vacuum tubes in much the same manner in which they are obtained with arcs, as described further on.

While this phenomenon has been employed in connection with radio receivers, it is more desirable to suppress it, as by some "losser" method which causes the energy to be damped out (as by a resistance connected in the grid circuit), to prevent the grid potential from becoming sufficiently positive to cause the oscillations to take place.

The foregoing phenomenon is not concerned with the electrons that pass through the grid and strike the plate directly from the filament. However, secondary emission also can take place from the plate and, if the grid is made more positive than the plate, electrons ejected from the plate will be drawn over to the grid.

59. Major Circuits of Triode.—The three-electrode vacuum tube has three major associated circuits, namely, the filament, the plate-to-filament, and the grid-to-filament circuits, commonly referred to as the filament circuit, the plate circuit, and the grid circuit, as in Fig. 99 wherein P is the plate-circuit milliammeter and g is the grid-circuit milliammeter or else microammeter. Each circuit has a resistance. The filament resistance is constant when the plate and grid potentials are constant, but it varies in large power tubes with variations in these potentials, evidently because sometimes there are more free electrons in the filament that at other times, or else their distribution varies, because of the time rate at which electrons are leaving the filament, the resistance varying inversely as the quantity of free electricity in a given length of conductor.

The resistances of the plate and grid circuits vary over wide ranges and are different for continuous currents than for alternating currents. The ratio of the voltage to the current strength in alternating-current circuits is the *impedance.* Hence the plate and grid circuits are said to possess impedance between the filament and the plate and between the filament and the grid.

The grid circuit is called the input circuit and the plate circuit is called the output circuit of the tube. Hence the ratio of the plate voltage to the plate current is the output impedance. For maximum results with a given plate voltage, the internal impedance between the filament and the plate should be equal to the impedance of the circuit outside of the tube between

the plate and the filament. For negative grid potentials, the continuous-current resistance between the filament and the grid is exceedingly great. The grid current strength varies approximately as the square of the positive grid potential.

Conductance is the ratio of the current strength to the voltage, being the reciprocal of resistance. Hence there is a plate-circuit conductance and a grid-circuit conductance.

Then there is a grid-to-plate circuit in such cases where secondary electrons move from the grid material to the plate, and *vice versa*, and when the plate is given a negative potential and the grid a positive potential, so that some of the electrons moving from the filament to the grid pass between the wires of the grid on their own momentum, only to be repelled by the negatively charged plate and attracted back to the grid, thus forming oscillating currents having frequencies approaching that of infra-red light.

60. Capacitance of Triode.—The simple three-electrode tube has many complex phenomena associated with it. It is a complicated electric condenser in that there are at least three capacitances to be considered which may have great effects upon its operation at radio frequencies, since then small condensers pass relatively strong currents. There are the filament-to-grid, grid-to-plate, and grid-to-plate-to-filament capacitances, with the plate and filament connected together through the "B" battery (Fig. 99) and external impedance.

Hence the internal input capacitance is that between the grid as one plate of the condenser and the filament and plate connected together as the other plate of the condenser, and power can be transferred from the plate circuit back to the grid circuit through this internal-capacitance coupling alone, it being sufficient to maintain electric oscillations when the grid and plate circuits are tuned to the same frequency and the capacitances of the tuning condensers are sufficiently small. The input capacitance makes the tuning of the input circuit depend to some extent upon the adjustment of the plate circuit; the negative resistance frequently causes undesirable oscillations, as previously mentioned, but the effect of this *mutual capacitance* has been neutralized, as in tuned radio-frequency amplifiers where the undesirable oscillations are apt to occur.

61. Heater Cathodes.—Three-electrode and other hot-cathode tubes are provided with electrically heated cathodes, the heater

being electrically insulated from the cathode, so that the alternating-current hum will not interefere with radio reception, in particular. Such tubes generally are graphically represented as shown in Fig. 102.

62. Tetrodes.—The four-electrode tube was designed by Hull, further to control the space charge and, therefore, the plate currents, by placing a shielding or screening grid between the usual control grid and the plate of the triode, thus preventing the electric field of the plate from affecting the control grid. Such tubes are termed screen-grid tubes. Relatively strong currents may be obtained if the positive potential of the control grid is made sufficiently great so that all of the electrons emitted from the filament are drawn toward it. These electrons constitute a space charge between the control grid and the screening grid while they are moving between the control grid and the plate and, being spread out, readily may be controlled by the screening grid. Thus large variations in the plate current are possible, but secondary electrons leave the plate and cause trouble.

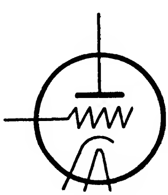


FIG. 102.—Graphical representation of heater-cathode triode. The filament or heater merely heats the cathode and has no direct electrical connection thereto.

By placing the screening grid around the plate (Fig. 103) it shields the control grid from plate-voltage fluctuations, an advantage being that, when the control grid has a potential tending to cause a strong current to flow, the resulting change in the plate potential has little of the effect on the plate current that it has in the triode, and it reduces the mutual capacitance of the tube, thus largely eliminating troubles due thereto. The voltage amplification of such a tube may be as high as 400, thus requiring fewer stages of amplification. Amplifiations of about a million times have been obtained with screen-grid tubes without the circuit going into oscillation.

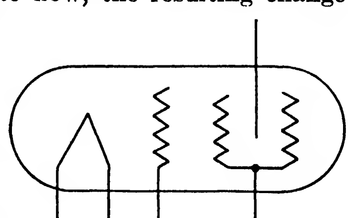


FIG. 103.—Tetrode or screen-grid tube.

63. Pentodes.—This five-electrode tube (Fig. 104) embodies a "suppressor" grid mounted between the control grid and the screening grid to prevent secondary electrons from leaving the plate, mainly to permit greater voltage swings to increase the

output of power tubes. It also has been found that the suppressor grid is useful in screen-grid tubes designed for high-frequency amplification.

64. Other Types.—There are many other types of electronic tubes, a number of which are described further on, but there are so many specific forms that a separate volume would be required to describe them. Some are several tubes combined in one with the interconnections included, as voltage and power amplifier tubes.

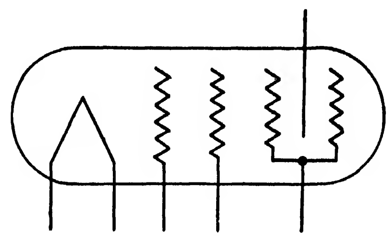


FIG. 104.—Pentode.

Attention is called to two types of tubes with outside electrodes. Glass is a solid solution, that is, it becomes more and more viscous with decreased temperature, somewhat like molasses. Lead glass contains lead. Donle placed the anode on the outside of a three-electrode radio tube and, after it had been operated for a considerable period, lead was found deposited on the under side of the anode or plate. Certain forms of electronic tubes have their grids placed on the outside of the glass tube. Deflecting plates, for deflecting cathode rays, also sometimes are placed on the outside of the tubes.

CHAPTER X

CIRCUIT PHENOMENA ASSOCIATED WITH ELECTRONIC TUBES

The list of electronic tubes is long and varied. There are two-, three-, four-, five-, and other multi-electrode vacuum tubes for radio and other purposes; two-, three-, four-, and other multi-electrode gas-filled tubes and lamps for various uses and kinds and types of illumination; various forms of light-responsive or photoelectric cells, either operating electromagnetic relays directly or through the intermediaries of vacuum or gas-filled tubes or lamps; x-ray; cathode-ray, and other forms of tubes, many of which are or may be combined in various combinations in a multitude of circuits. There appears to be no end to the possible and useful combinations, only a limited number of simple circuits being shown in this volume. In contrast to this complexity of tubes, circuits, and devices, there are but three fundamental circuit phenomena to be considered in connection with them. These are resistance, inductance, and capacitance, all of which are found, at least to some extent, in every form of electric circuit. The term "capacity" seems objectionable to some because of its universal use, as cubical content; carrying power; productive power; talent; specific position; legal qualification, and so on. The term "permittance" also is used instead of capacity in an electrostatic sense. Nevertheless, the term is universally used in connection with couplings and therefore will be used herein in connection with such circuits.

65. Circuit Phenomena.—Self-inductance and capacitance have been discussed in detail in previous chapters, but very little is known regarding the true nature of electric resistance in solid metals, although the general behavior of large numbers of electrons in vacuum tubes gives one the notion that when electrons travel through space freely, even for small distances, and then collide with atoms they knock out secondary electrons,

produce x-rays, and certainly produce heat. The atoms are closely packed together in solid metals and it has been suggested that the valence electrons continuously move about from atom to atom, thus forming a sort of gas which drifts under the influence of a difference of potential to form an electric current.

From the energy viewpoint, however, it is definitely known that in most metals the resistance increases with temperature and, therefore, with the heat-energy content, and that the greater the resistance becomes the more rapid is the conversion of electrical energy into heat for a given current density (squared). Thus, when the current strength is constant in a metal conductor from which no heat can escape, the more heat there is stored within it the more difficult it becomes to store more heat in it, that is, the voltage must be increased as the heat is stored and the temperature increased.

A number of estimates have been made by various physicists, using various methods, as to the probable number of free electrons per atom in various metals. These estimates vary from several electrons per atom to several atoms per electron. It is believed that most physicists, for want of more accurate knowledge, assume that there is, on the average, about one free electron per atom and, since the number of atoms per cubic centimeter in metals is of the general order 0.05 trillion trillion, if the free-electron drift should be made 1 cm per sec., there would result the enormous current density of about 8,000 amp. per sq. cm, or about 50,000 amp. per sq. in., of conductor cross section. It follows that when the cross section of a metal conductor is such that there are about 6.281 billion billion (the number of electrons in a coulomb) atoms per centimeter length of conductor, the current strength would be about 1 amp. when its velocity was 1 cm per sec.

As the temperature T of a metal wire increases, its total heat content W and its electrical resistance R also increase. Thus the total heat content increases from W_1 to W_2 joules, and the resistance increases from R_1 to R_2 ohms, when the temperature increases from T_1 to T_2 deg. Early in 1932, the author[1] investigated a large number of pure metals and found that when a current of mean strength 1 amp. was allowed to flow in a wire for exactly 1 sec, and then abruptly stopped, thus permitting exactly

[1] See also *Journal* of the Franklin Institute, November, 1933. In this article, the temperature T_1 is absolute zero.

1 cmb of free electricity to flow through every plane in the cross section of the wire during that second, the increase in heat content $W_2 - W_1$ (or ΔW) and the increase in resistance $R_2 - R_1$ (or ΔR), while having different dimensions, were numerically equal over the common temperature interval $T_2 - T_1$ (or ΔT) at a critical cross section of metal wire, in which case the number of atoms per linear centimeter of wire turned out to be of the same general order as the number of electron charges in a coulomb (6.281 billion billion). Since this appears to be entirely new, those familiar with such calculations may try it for themselves, as briefly outlined in the accompanying footnote,[1] where the mean current strength is meant.

66. Resistors, Reactors and Condensers.—That which is designed to contain resistance is a resistor; that which is made to contain self-inductance is an inductance coil or a reactor, whether air-cored or iron-cored; and that which is constructed to contain capacitance is a condenser. All parts of an electric circuit contain some resistance, self-inductance and capacitance.

No body or part of a circuit can be given a potential without giving it a charge, and there can be no charge without a charging current, that is, electrons must move to, from, or within a body in order that said body may become electrically charged. Hence when a grid, for example, is given a potential or increase in potential it always is accompanied by a charging current in

[1] By Joule's law, $w = \Delta W = I_m^2 R_m t$ joules, wherein W is the total heat energy (with that required to expand the metal) in a wire, I_m is the current strength in amperes, R_m is the mean resistance in ohms over the temperature interval $\Delta T = T_2 - T_1$ deg., and t is the time interval in seconds. Hence it follows that when $I_m = 1$ amp. and $t = 1$ sec., $\Delta W = R_m = (C_m/A)m\Delta T$ joules, wherein $C_m = \frac{1}{\Delta T}\int_{T_1}^{T_2} C_p dT$ is the mean specific heat in joules per gram atom per centigrade degree, A is the atomic weight, m is the mass of metal in grams, ΔT is the increase in temperature in centigrade degrees, and C_p is the specific heat in joules per gram atom per centigrade degree at any given temperature. Consequently, *when*

$$\Delta R = R_2 - R_1 = R_m, \quad \Delta R = (C_m/A)m\Delta T = (L/s)\Delta\rho = (C_m/A)Lsd_m\Delta T,$$

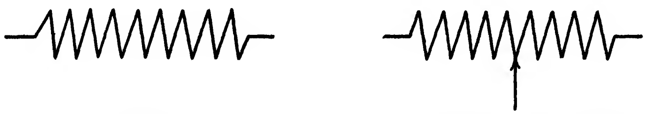
wherein ρ is the volume resistivity of the metal in ohm-centimeters, d_m is the mean density, and s is the cross-section of wire for the condition that $\Delta R = R_m = \Delta W$, whence

$$s = \sqrt{\frac{\Delta\rho}{\Delta T}\frac{A}{C_m d_m}} \text{ sq. cm.}$$

The number of atoms per linear centimeter in a wire of cross section of s sq. cm is $N/L = N_0 s d_m/A$, wherein $N_0 = 6.061 \times 10^{23}$ (Avogadro's number).

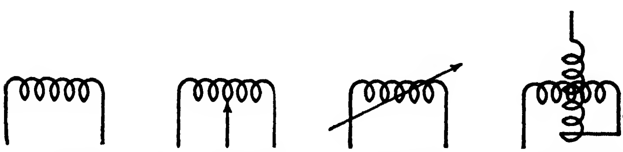
the grid circuit, however brief and small. Similarly, there always is a discharging current when bodies are discharged.

Impedance, the ratio of the voltage to the current strength, is anything that tends to impede the flow of electricity. It may consist almost entirely of electric friction, or electromagnetic



A. Fixed. *B*. Adjustable or variable.

FIG. 105.—Resistors.

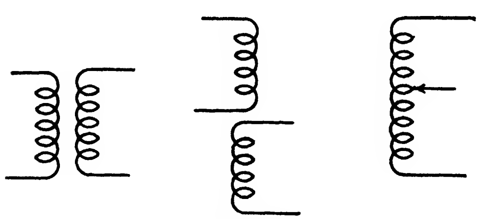


A. Fixed. *B*. Adjustable. *C*. Variable. *D*. Variable.

FIG. 106.—Air-core inductance coil, inductor, or reactor.

A. Fixed. *B*. Adjustable.

FIG. 107.—Iron-core reactors.

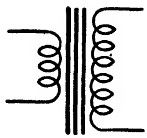


A. Concentrically wound type. *B*. Axial type. *C*. Auto type.

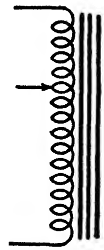
FIG. 108.—Air-core transformers or couplers.

inertia, or of electrical elastic effects, due to resistance, self-inductance and capacitance, respectively, or it may consist of any two or all three effects.

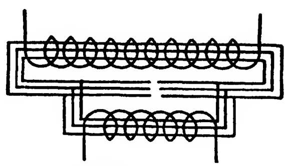
67. Graphic Symbols.—The symbols used by power engineers and by radio engineers differ somewhat. Thus what the radio engineer would consider as a resistor the power engineer might consider a coil. Since this volume deals with electronic details, the radio engineer's symbols herein are employed. Some of



A. Common type.

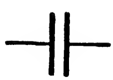


B. Autotransformer.



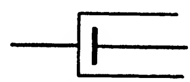
C. Leakage-reactance type.

FIG. 109.—Iron-core transformers or couplers.



A. Fixed.

B. Variable.



C. Shielded.

FIG. 110.—Condensers.

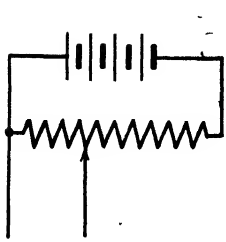
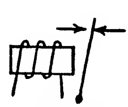
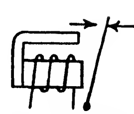


FIG. 111.



A. Ordinary.



B. Polarized.

FIG. 112.

FIG. 111.—Potentiometer, for obtaining various voltages from the voltage drop along a resistor.
FIG. 112.—Relays.

A

B

C

D

E

FIG. 113.—*A*. Alternating-current generator. *B*. Direct-current generator. *C*. Ground connection. *D* or *E*. Telephone receivers of loud speaker. *A* and *B* also represent motors when *M* is marked upon them.

these symbols are shown in Figs. 105 to 114. Other symbols appear in the diagrams throughout the volume.

68. Effects on Alternating and High-frequency Currents.—Suppose we had an electric generator that we could run at any desired speed, from a few cycles per second to radio frequencies of hundreds of thousands of cycles per second, and still keep the voltage constant by some kind of voltage regulator. It is not practicable to do this, but it will serve in illustrating the effects of resistance, self-inductance, and capacitance. We shall connect an ammeter in the test circuit so that we may note how the current strength varies with the frequency, or so that we may keep the current strength, instead of the voltage, constant.

V. Voltmeter. *A*. Ammeter.

FIG. 114.—Meters, in general. However, in this volume the symbols given in the table on page 9 are generally employed. When *g* is used alone, a galvanometer generally is referred to.

First we connect a long piece of resistance wire, whose resistance does not change very much with temperature, in the test circuit. We find that while the resistance increases with frequency, it is increased only a relatively few times.

We next connect an iron-cored reactor in the test circuit and try to keep the current strength constant as we increase the frequency by increasing the speed of the generator. We find that we have to keep taking out iron from the core as the frequency increases until, when we obtain radio frequencies, there is no iron left in the coil.

Next we try connecting a variable condenser (of a peculiar design) in the test circuit. It is so constructed that we can remove small sections of it as the test progresses. We try to keep the current strength constant as the frequency increases by removing the small condenser sections, one at a time. When we obtain radio frequencies, only one of the little sections remains, but we have the same current strength in the circuit as we had at the lower frequencies.

Thus we learn that while we need more material in electric conductors or resistors for equal lengths and resistances at radio frequencies, since we must increase their cross sections to keep the resistance constant, we need less and less iron and condenser material as the frequency increases. That is why the components of high-frequency apparatus are so much smaller than

in low-frequency devices of the same voltage and current rating. It also explains why the sizes of high-speed generators, motors, turbines and other rotating and reciprocating machinery of given ratings decrease as the speed increases.

A direct or continuous current is substantially a zero-frequency current after it once gets going. An inductance coil or reactor offers only the resistance of its coiled conductor to the flow of continuous currents but much more opposes currents whose strengths vary. Hence it opposes the starting and stopping of a continuous current and it opposes the flow of alternating currents in direct proportion to their frequencies through the reactive voltages produced thereby. Thus a coil which would offer only 0.1 ω impedance to a 60-c current might offer an impedance of more than 1,600 ω to a million-cycle current.

A good condenser offers millions of ohms resistance to a continuous current, but offers less and less impedance to an alternating current as its frequency increases. Thus a condenser of such small capacitance as to offer an impedance of more than 1,600 ω to a 60-c current might offer only 0.1 ω to a million-cycle current.

A resistor offers more resistance to a high-frequency current than to a low-frequency current or direct current, apparently because the free electrons are driven toward the surface of the conductor or the resistor material by the internal alternating pressure, thus decreasing the effective cross section of the material. Hence, hollow conductors may offer no more resistance than solid conductors of equal diameters to high-frequency currents.

69. Uses of Resistors, Reactors, and Condensers.—From the foregoing and for a given alternating-current strength, the voltage across an inductance coil or reactor increases with the frequency, while that across a condenser decreases with the frequency. It follows that inductance coils or reactors may be used to block the passage of high-frequency currents while permitting continuous or low-frequency currents to pass, and that a condenser may be employed to block the passage of continuous or low-frequency currents while permitting high-frequency currents to pass. Hence such terms as "blocking condenser," "by-pass condenser," and so on. An example of the simultaneous employment of both of the above functions is shown in Fig. 115.

As previously stated, it also is possible to make the capacitance of a condenser and the self-inductance of a reactor such that when they are connected together and a current of a given frequency flows in the circuit, the voltage of the reactor shall exactly balance that of the condenser, just as the force of a balance wheel exactly balances that due to the hairspring in a clock or a watch, in which case the only impedance offered to the current is the resistance of the circuit, but there always are some losses in the iron (if any) of the reactor and in the dielectric of the condenser.

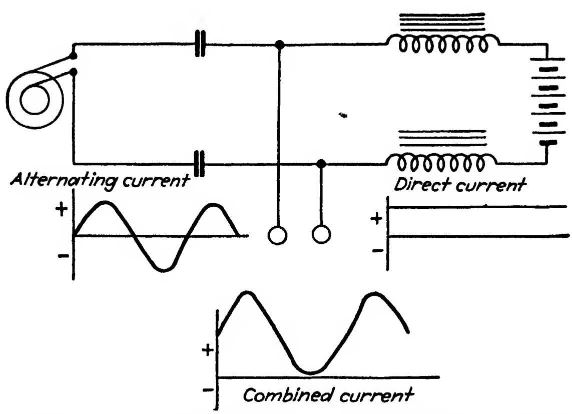


FIG. 115.—Method of combining direct and alternating (as high-frequency) currents. Compare with Figs. 72 and 127.

This is the condition of resonance which obtains when the square root of the product of the self-inductance of the reactor and the capacitance of the condenser is equal to *n* times the reciprocal of the frequency in cycles per second, wherein *n* is a number (described below) depending upon the units employed. Obviously, the self-inductance of the reactor and the capacitance of the condenser may be varied, providing their product is constant, without affecting the natural oscillation frequency, just as the elasticity of a hairspring is increased as the mass of a balance wheel is decreased so that the oscillation frequency shall remain constant, as known to clock- and watchmakers the world over for a great many years.

The unit of self-inductance is named in honor of Henry, the unit commonly used in practice being but one-thousandth of a henry and called the millihenry. The unit of capacitance

is named in honor of Faraday. The microfarad (one-millionth of a farad) is the unit commonly used in practice. Both of these units are further subdivided for use with high-frequency currents.

The condition for resonance when the frequency is 60 c per sec. is that the product of the self-inductance in millihenries and the capacitance in microfarads shall be 7,050, while for 1 million cycles per second it is only 0.00263. These products are called the *oscillation constants* corresponding to given oscillation frequencies.

While the alternating voltages and current strengths vary to and from positive and negative maximum and zero values during any cycle, they also have *effective* values which are employed in exactly the same manner as are direct or continuous voltages and current strengths. One effective ampere is equal to 0.707 times the maximum, or to 1.11 times the average, current strength during any half-cycle. It is the current strength that will produce heat at the same time rate as will 1 amp. of direct current. In a similar manner, 1 effective volt is that required to produce an effective current strength of 1 amp. when the resistance or the impedance is 1 ω.

The impedance of a reactor is equal to 0.00628 times the product of the self-inductance in millihenries and the frequency in cycles per second. The impedance of a condenser is found by dividing the number 1,590,000 by the product of the capacitance in microfarads and the frequency in cycles per second. Since the effective voltage across each is equal to the product of the effective current strength and the impedance, it is seen that, for a given current strength, the larger we make the self-inductance and the smaller we make the capacitance, the greater will be the voltage across the reactor and the condenser, the two voltages always being equally opposed when resonance occurs. The unit of impedance is the ohm.

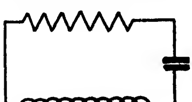
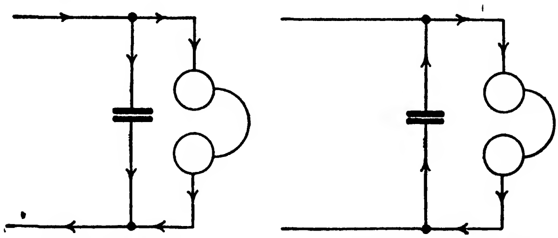


FIG. 116.—Resistance, self-inductance, and capacitance in series.

Hence, in a circuit containing a resistor, a reactor, and a condenser in series (Fig. 116), when resonance occurs the current strength in amperes will be equal to the ratio of the effective voltage impressed upon the circuit (as through induction) to the resistance in ohms of the resistor and the connecting wires. Having found the current strength, the effective

voltages across the reactor and the condenser may be calculated by multiplying the impedance of each by the effective current strength.

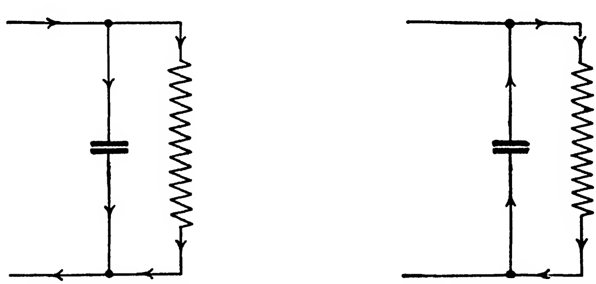
With the above units of self-inductance and capacitance, the value of n, referred to above, is 5,020. As an example, if the



A. Charging condenser. *B.* Condenser discharging.

FIG. 117.—The condenser is charged by a pulse, the energy of which mostly is stored in the condenser and then discharged into the telephone receivers, relay, or other device. Note that while the direction of the current reverses upon the discharge of the condenser it continues in the same direction through the telephone receivers or other reactor.

frequency is 60 c per sec., the product of the self-inductance in millihenries and the capacitance in microfarads required for resonance is equal to 83.7 squared = 7,050, as in the foregoing. Thus it is a simple matter to find the oscillation constant for any desired frequency.



A. Charging condenser. *B.* Condenser discharging.

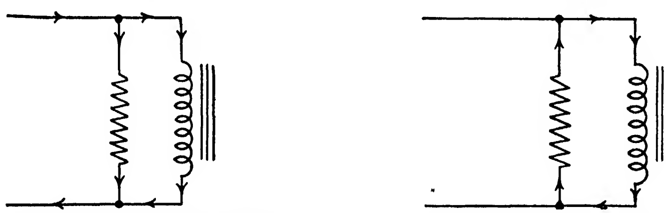
FIG. 118.—The discharge of the condenser does not affect the direction of flow of the current in the resistor.

Other uses of resistors, reactors, and condensers consist in connecting a condenser across a telephone receiver that will not respond to high-frequency pulsating unidirectional currents because of the self-inductance of its iron-cored coils (Fig. 117). Each pulse charges the condenser and also starts flowing in the telephone receiver. An electromagnetic relay (Fig. 112)

may be operated in a similar manner. As the pulse passes, the condenser immediately discharges its energy into the coils of the telephone receiver or relay, thereby maintaining the current in said coils until another pulse arrives or the condenser is completely discharged.

Since time is required to convert electrical energy into heat, when a resistor is connected in parallel with a condenser (Fig. 118), the latter may be very quickly charged without much energy being converted into heat in the resistor. When the voltage is discontinued, however, the condenser discharges its energy into the resistor.

Likewise a resistor may be connected in parallel with a reactor (Fig. 119) to receive its energy when the voltage falls, thereby preventing sparking or arcing at switch or relay contacts.



A. Electromagnetically charged reactor. *B.* Reactor discharging.

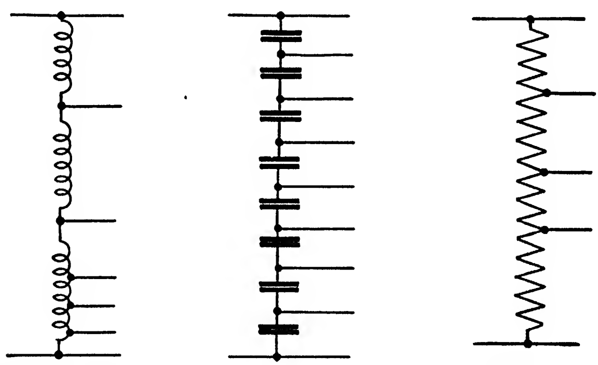
FIG. 119.—The discharge of the reactor keeps the current flowing in the same direction therein but reverses the direction of the current through the resistor and any small electromagnetic device connected in series with the resistor.

Other combinations of resistors, reactors and condensers are made, a resistor being the only device of the three wherein all of the electrical energy may be converted into heat. Electrical oscillations always tend to occur in circuits containing resistance, self-inductance, and capacitance.

A resistor converts electrical energy into heat which cannot be reconverted into electrical energy thereby in the circuit; a reactor abstracts electrical energy from the circuit and stores it as magnetic energy, *only* while the current flows, but a condenser abstracts electrical energy from the circuit and it may be stored therein as long as may be required practicably, when it may be again restored to the same or another circuit. The condenser is the only one of the three devices wherein energy may be stored and then transported while stored after the manner of a storage battery. A coil immersed in liquid helium was given an impressed voltage through electromagnetic induc-

tion and the coil with the current flowing in it then was transported from Holland to England by airplane, the current still flowing in the closed coil upon arrival. But this is a very unusual condition. A permanent magnet also contains stored magnetic energy.

Since resistors, reactors, and condensers may have differences of potential across their terminals, when any number of the devices are joined in series in a circuit, they may be used as voltage dividers by tapping between their terminals, as in Fig. 120, because there is a fall in potential from device to device. Thus voltage dividers purposely are made in this general manner.



A. Reactor type. *B.* Condenser type. *C.* Resistor type.
FIG. 120.—Voltage dividers.

70. Phase Shifting.—The term "phase" means "step" in the respect that a synchronous motor is in step with the generator driving it when they are in synchronism or in phase. In a similar manner, the alternating current and voltage are in phase when only electric resistance is present in a circuit, or when resonance occurs, whereas they are not in phase or in step under other conditions, as when there are resistance and capacitance or resistance and self-inductance in the circuit. Figures 64 and 73 should be consulted in this connection.

Power is the time rate of conversion of energy. The power factor of an alternating-current circuit is the ratio of the total current strength to the heating or working current strength. In the circuits represented by Figs. 64 and 73 the power factor is substantially zero because substantially no energy is being converted into heat or heat-producing work, the only transfer

of energy being into the reactor or the condenser and back again to the line, the generator and the turbine driving it doing substantially no work because the *effective* power is substantially zero.

It follows that by means of resistors (or incandescent lamps) and condensers, or by means of incandescent lamps (or resistors) and reactors, the effective power in a circuit may be varied from near zero to a maximum merely by varying the capacitance or the self-inductance. Hence, by shifting the phase in this manner, the amount of effective power going to incandescent lamps and the like may be controlled.

Phase shifting is particularly adapted to the control of lighting in theaters where large banks of resistors, with their consequent energy losses and expense, otherwise might be used.

Considering the incandescent lamps as a resistor, when either a variable reactor or a variable condenser is connected in series, it is obvious that reactive voltages may be set up by them which shall oppose the line voltage in varying degrees and, therefore, control the current strength in the lamps, although actually it is accomplished in a much better manner by means of electronic tubes, as discussed in Art. 112.

CHAPTER XI

ELEMENTS OF ELECTRONIC TUBE CIRCUITS

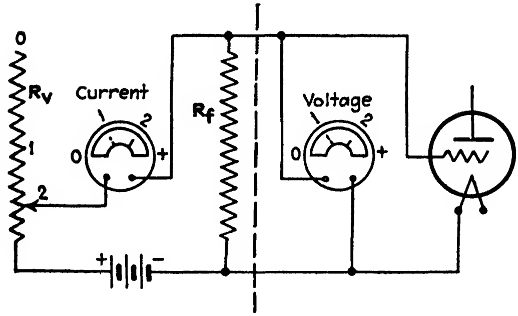
Probably there are few more ways of obtaining substantially the same results by circuit "hook-ups" than there are in radio-frequency apparatus. The use of pentodes and tetrodes is changing and simplifying the forms of circuits used. The principles employed in radio apparatus also are useful in large numbers of industrial and other applications. The present chapter treats of the elements of such circuits and a few of their applications.

71. Source Circuits.—In a direct-current circuit containing only resistors connected in series the entire counter-voltage, back pressure or fall in potential is divided among the various resistors, the voltage across each resistor being directly proportional to its resistance. Hence, in such a circuit containing only a fixed resistor R_f and a variable resistor R_v (Fig. 121), as the resistance of the variable resistor is varied, the current strength in the entire circuit changes and it changes the voltage across each resistor. In this manner the voltage across a fixed resistor may be varied to control the grid potential, that is, the difference of potential between the grid and the filament or cathode of an electronic tube or that of a lamp, by using the fixed resistor as a *coupling* between the source and control-grid circuits.

Such a circuit herein is termed a source circuit because it is the circuit containing the source wherein the action is started and passed on to the control grid in the form of a change in potential. This is the sole function of the source circuit, which has many forms, with respect to the apparatus to be controlled. Source circuits may be of the direct, impulse or transient, alternating or high-frequency types.

72. Direct-current Source Circuits.—In Fig. 121 and the following illustrations, the current and voltage indicators merely illustrate in which directions the needles move as the current strength and the grid potential change with corresponding

changes in the source circuit when the control moves from any point 0 to any other points 1 and 2, or when time varies from



Source circuit. Control-grid circuit.

FIG. 121.—Direct-current source circuit for varying the grid potential, making it more or less positive in this particular case. When the resistance of resistor R_v is varied, the voltage (the grid potential) across resistor R_f is varied. The current and voltage indicators merely illustrate the fact that the current strength in the entire source circuit and the grid potential increase with a decrease in the resistance of resistor R_v. The numerals outside the indicators refer to resistor taps in this particular case.

instant 0 to any other instants 1 and 2. They also indicate polarities, but they do not indicate actual values.

When a reactor L and a resistor R (Fig. 122) are connected in series in a direct-current control circuit, the grid potential is made a maximum in one direction, then reduced to zero, and

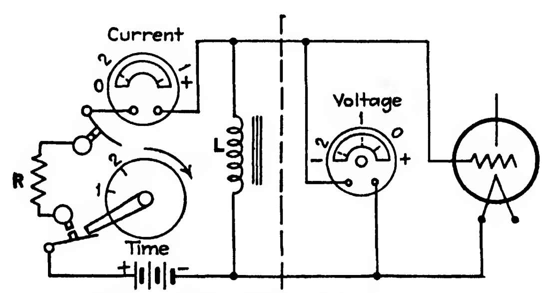


FIG. 122.—A method of impressing pulses of potential on the grid The needle of the voltage indicator swings to the right on positive pulses and to the left on negative pulses, its "off" position being at the middle of the scale. The numerals outside the indicators refer to instants in this case. Thus while the current strength rises to a maximum as time elapses and falls back toward 0 as the circuit again is opened, the maximum grid voltage occurs when the source circuit first is closed, falling to 0 at instant 1, and then reversing to a maximum value when the circuit is opened.

next made a maximum in the opposite direction, merely by closing and opening the source circuit, the resistor acting as a

"ballast" to prevent too great a current from flowing. At instant 0, when the contacts are brought together to close the circuit, substantially all of the fall of potential is across the reactor, but by instant 1 the storage of magnetic energy in the reactor practically is completed and substantially all of the fall in potential is across resistor *R* where the energy of the current is being converted into heat.

At instant 2, when the contacts gradually are separated, the reactor *L* begins discharging its energy in the same direction in which the current is flowing, thereby tending to increase the current strength which, however, falls to zero when the reactor completely has discharged its energy, most of which is converted into heat in the spark between the contacts as they separate.

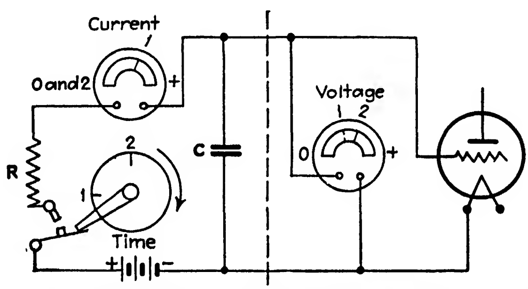


FIG. 123.—Direct-current means of obtaining a gradually growing and fixed grid potential. The greater the resistance of resistor *R* the greater will be the time interval required for the charging of condenser *C*. The numerals outside the indicators refer to instants.

Thus, either a positive or a negative pulse or surge of grid potential may be obtained by closing or opening a direct-current source circuit, depending upon the polarity of the battery in said circuit. Such a pulse may be caused to operate a lock-in relay of either the electromagnetic or grid-glow type.

In Fig. 123 is shown a direct-current source circuit with a condenser *C*, in series with a resistor *R*, for coupling the grid-control circuit with the source circuit. At any instant 0, as the contacts are brought together to close the circuit, there is a rush of current whose strength is limited only by the resistor *R*, across which substantially the entire fall of potential occurs. At instant 1 and thereafter, the entire fall of potential will be across the condenser.

In this manner the time interval between instants 0 and 1 may be varied as desired by varying the resistance of resistor

R, that is, by using resistors of various resistances or of variable resistance, since a resistor is a timing device permitting the electrons within it to move, on the average, only at definite velocities, as determined by the resistance of the resistor and the voltage across its terminals. Hence, if the resistance of resistor R is made relatively great, a relatively large time interval will be required for condenser C to be charged to a given difference of potential, particularly if its capacitance be relatively great. The capacitance also may be varied if desired.

Thus the grid potential may be caused to increase at substantially a fixed or linear time rate, and when a critical difference of potential is reached, it may be caused to operate either an electromagnetic or a grid-glow relay which, in turn, will cause a current to flow in another circuit, or, by reversing the polarity of the battery, a current in the plate circuit of a triode slowly and uniformly may be stopped, said condition being maintained until condenser C is either partially or completely discharged, as through a separate resistor.

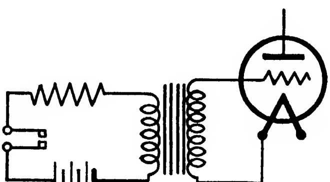


FIG. 124.—Use of a transformer for coupling the source and control-grid circuits. The contacts shown at the left merely represent some means of varying the current strength in the source circuit.

In Fig. 124 is shown a transformer coupling between the source and grid-control circuits. The conditions are identical with those in Fig. 122, except that the grid potential at any instant is the reverse of that in Fig. 122, unless the direction either of the secondary or of the primary winding is changed or the terminals of one or the other interposed.

73. Grid Bias.—When a small ("C") battery is connected in series with the grid in any of the above circuits, the grid is said to be biased because either a greater or a smaller negative or positive potential is required for the operation of a three-electrode electronic tube or lamp, depending upon the voltage and the polarity of the "C" battery. If the positive terminal of the "C" battery is connected to the grid, the grid is said to have a positive bias or, if the negative terminal is connected to it, a negative bias.

74. Electronic Tubes as Resistors.—The resistance of a vacuum tube varies with the number of free electrons in its space charge. Hence a two-electrode vacuum or gaseous-dis-

charge tube may be employed as a resistor. In a vacuum tube, the resistance may be varied up and down by adjusting the filament current strength, thereby making the vacuum tube act as a combined switch and variable resistor. The action of the gaseous-discharge tube is somewhat different. Thus the vacuum tube known as the photoelectric tube acts as a switch or as a variable resistor when light falls upon its cathode in varying intensities and, when connected in a source circuit, is able to control large amounts of power through the intermediary electronic tubes and associated circuits. Such electronic tubes are discussed in detail further on (see Index).

75. Alternating-current Source Circuits.—These include both low- and high-frequency circuits. Thus a radio antenna circuit is a source circuit which is energized by electromagnetic waves traveling through space, much as a photoelectric circuit is energized by light (also electromagnetic) waves traveling in space. Either resistors, reactors, condensers, or transformers may be used as couplings for impressing alternating potentials upon grids. A typical antenna circuit is shown in Fig. 125.

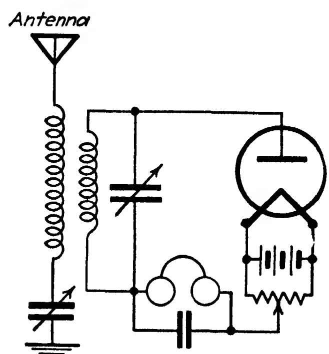


FIG. 125.—A method of using a diode as a detector.

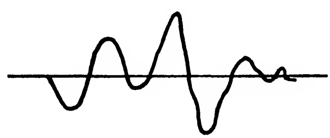
76. Source Circuit Containing Variable Capacitance.—When oscillating currents are established in a source circuit, the frequency may be varied by changing the thickness, width, or composition of the dielectric material between the condenser's plates. As the frequency increases at constant voltage, the current strength increases as resonance is approached. Hence materials are tested and processes controlled by passing said materials between the condenser's plates, as on a belt.

77. Vacuum Tubes as Rectifiers.—When a diode is connected in series in an alternating-current circuit, only every other half-wave of voltage will produce a current in the circuit because electrons cannot flow from the cold anode while they can flow from the hot cathode of the tube when rated voltage is applied to it, as previously discussed. This principle also

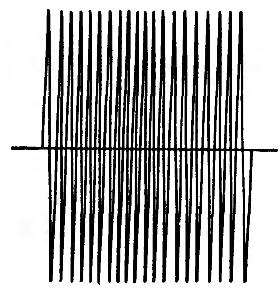
is carried out in large power gas-filled tubes, but attention here is particularly called to it in connection with radio reception.

78. Vacuum Tubes as Radio Detectors.—Although the continuous or undamped waves from the broadcasting stations are modulated so as to have varying amplitudes caused by the shapes of the "sound-current" waves superposed upon them (Fig. 126), interrupted-wave trains of constant amplitude herein are used as illustrations.

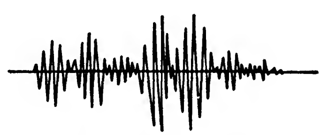
The simple circuit in Fig. 125 consists of a tuned antenna circuit inductively coupled with an oscillating circuit in tune



A. Audio-frequency "voice" current.



B. High-frequency carrier waves.



C. Modulated waves.

Fig. 126.—Modulating high-frequency radio currents.

with it, whereby potentials alternately and periodically are impressed upon the filament and the plate of the diode or two-electrode vacuum tube (Fleming valve) herein used as a detector, the rectifying action being to permit unidirectional pulses to flow in the tube-and-telephone-receiver circuit during one-half of each cycle of the high-frequency radio current whose strength varies with the strengths or amplitudes of the incoming waves. Thus the condenser in parallel with the telephone receivers is charged and then discharged into the telephone receivers in the manner described in Art. 69 (Fig. 117).

In one method of detection the three-electrode vacuum tube, or triode, depends upon an increase in the average plate current,

while in the one most commonly used there is a decrease in the average plate current, the operation of the telephone receivers depending upon the change in the strength of the plate current which normally flows in their coils.

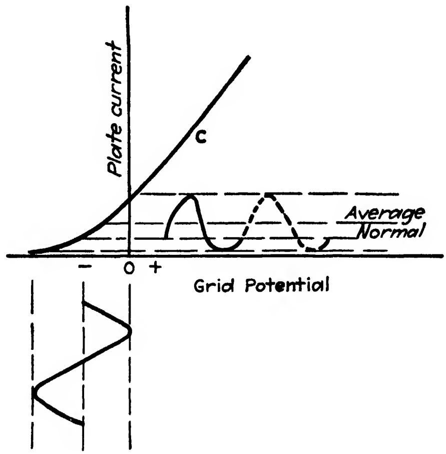


FIG. 127.—Principle of detecting with negative grid bias by increasing the average plate current above the normal plate current. See also Figs. 72 and 115.

In the first method, which has the disadvantage that the normal grid potential is rather critical, the increase in the average plate current due to variations in the grid potential

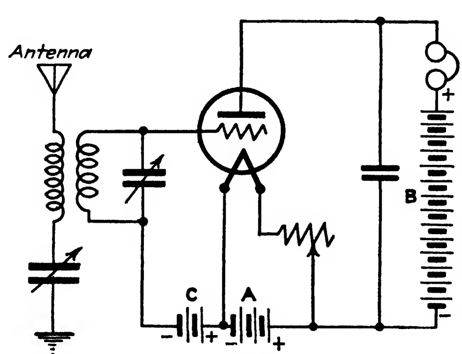


FIG. 128.—Method of utilizing a triode as a detector by increasing the average plate current.

cannot be obtained in the straight portion of the plate current-grid potential curve (Fig. 127, taken from Fig. 100 and exaggerated for clarity), since the increase in the plate current

would be equal to the decrease in said current during any cyclic change in the grid potential. Consequently a curved portion of the curve must be used so that the increase in the plate current during any half-cycle will be greater than the decrease in said current during the following half-cycle. In order to accomplish this, it is necessary to give the grid a negative bias, as by means of the "C" battery in Fig. 128, grid potential always being reckoned from the negative side of the filament.

Referring to Fig. 127, when the grid potential swings through the negative half-cycle, the plate current is not reduced as much as it is increased during the positive half-cycle of the grid potential. Hence the average plate current is increased, thereby actuating the telephone receivers. If the wave train is modulated, as by the human voice (Fig. 126), that voice will be heard in the telephone receivers.

This current is nothing but an alternating current superposed upon a continuous current, as in Figs. 72 and 115. The alternating component of this current cannot flow in the coils of the telephone receivers, nor is it desired there. A by-pass condenser is, therefore, shunted across the telephone receivers, "B" battery, and all, through which the alternating component flows, leaving only the unidirectional component of the varying plate current in the telephone-receiver coils. If the distributed capacity in the coils of the telephone receivers was great enough, the by-pass condenser would not have to be used,. but the coil capacity aids in the by-passing of the high-frequency component around the coils.

The second method, schematically shown in Fig. 129, employs a small condenser connected in series with the grid which requires a positive bias. Hence this method is known as detection with a grid condenser. It is brought about by employing the straight portion of the plate current-grid potential curve. Therefore the normal grid potential is not so critical as in the first method.

The positive grid bias is emphasized by the polarities of the "A" and "C" batteries which are reversed with respect to those in Fig. 128. When the *a* side of the grid condenser becomes positively charged due to the swing of the oscillating current through a positive half-cycle, thus being robbed of some of its electrons, other electrons are attracted from the grid to the *b* side of the grid condenser, thus giving the grid a positive charge and a positive potential. The grid then attracts to itself electrons from the

space charge, thereby increasing the charge on the *b* side of the grid condenser. When the *a* side of the grid condenser becomes negatively charged due to the swing of the oscillating current through a negative half-cycle, the electrons on the *b* side of the grid condenser are repelled to the grid, thus negatively charging the grid beyond its normal value and causing a corresponding decrease in the strength of the plate current, which has the same effect on the telephone receivers as has an increase in the average plate current.

Otherwise the two methods embody the same general principles, the straight portion of the characteristic curve *C* in Fig. 127 being used instead of the curved portion. The resistance *r* (Fig. 129)

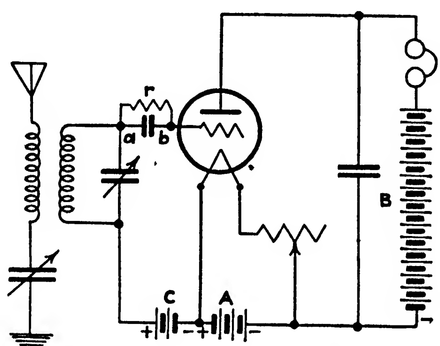


FIG. 129.—Detecting with a grid condenser by giving the grid a positive bias and decreasing the average plate current below the normal plate current.

drains off the charge of the grid condenser during low-potential intervals of the oscillating current and thereby maintains normal operation.

79. Direct-current Amplifiers.—While a single tube amplifies the grid current in the respect that, when a very weak current flows in the grid or input circuit a much stronger current may be made to flow in the plate or output circuit through the corresponding changes in the grid potential, the greater changes are produced through coupling the plate circuit of the first to the grid-control circuit of a second, and so on through as many stages as may be required or which will remain stable without the circuits oscillating due to the capacitance between the elements of the tubes, as described in Arts. 58 and 60.

Figure 130 shows a resistance-coupled amplifier suitable for operating a relay with currents amplified from the feeble currents

obtained from a photoelectric cell. Thus a current having a strength of only a few microamperes functions through the amplifier to operate a relay requiring several milliamperes for its operation, the overall gain through amplification being about as the square of the amplification constant μ for two stages, the cube

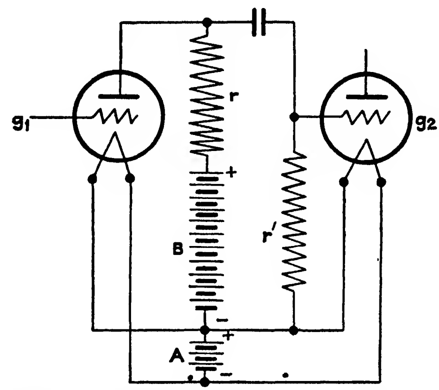


FIG. 130.—Schematic circuit of a resistance- or impedance-coupled amplifier.

of μ for three stages, and so on. Hence if the amplification constant μ of a tube is 7, the overall amplification with two stages will be 36; with three stages, 196; with four stages, 1,176, and so on.

80. Audio-frequency Amplifiers.—After detection, the audio-frequency or voice currents may be amplified by one or more

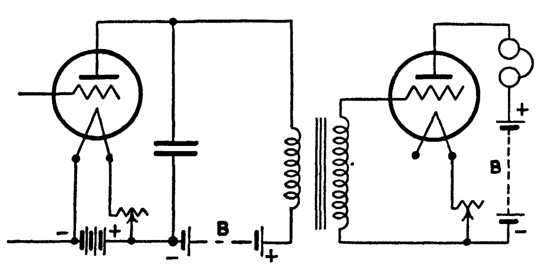


FIG. 131.—Transformer-coupled audio-frequency amplifier. The tube at the left is the detector tube. In practice the two "B" batteries here shown are the same battery.

stages of amplification, as in Fig. 131, wherein iron-core transformers are employed, the primary coil taking the place of the telephone receivers shown in Fig. 128. The pulsating current in the primary of the first transformer produces an alternating voltage in the secondary coil; wherefore thereafter alternating

currents are amplified. In practice the battery in the telephone-receiver circuit is the same battery ("B") in the detector output circuit.

The average human ear can hear vibrations only over the range 10 to 18,000 c per sec. A band from 30 to 7,000 c per sec. has been found ample for excellent transmission in broadcasting. These are the audio frequencies superposed upon the radio frequencies which, in the case of Station WJZ, for example, is 760,000 c (760 kc) per sec.

81. Radio-frequency Amplification.—In many broadcast receivers the high-frequency currents first are amplified, then detected, and converted into audio-frequency currents which are further amplified. Radio-frequency amplification may employ

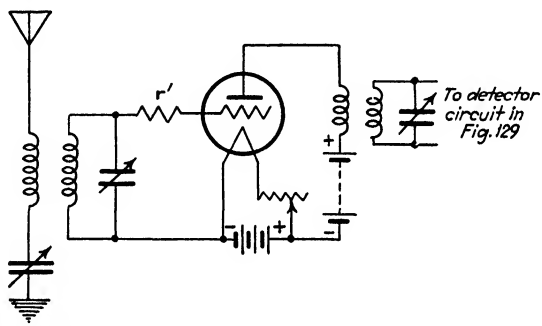


FIG. 132.—Single-stage amplifier between antenna and detector circuits.

either tuned or untuned radio-frequency coupling, only the former being discussed herein. Such an amplifier circuit is shown in Fig. 132, wherein resistor r' is employed in one "losser" method to damp out the energy sufficiently to prevent oscillations being established due to the tube capacitance. There are many other forms of circuits and methods designed to amplify the signals in a stable manner.

82. Amplifier Couplings.—The three principal methods of coupling vacuum tubes in an amplifying system are by transformer, by resistance, and by impedance. Capacity couplings also have been used. The transformer coupling has the advantage that for a given number of stages the amplification may be greater than in the other forms owing to the turn ratio, or ratio of transformation, of the transformer; that is, the voltage may be stepped up by using, for example, three times more turns in the secondary than in the primary coil. But there is apt to be distor-

tion in improperly designed iron-core audio-frequency transformers, *whereas the turn ratio may be increased and distortion* will be of little consequence in cases where it is desired only to operate a relay of some kind, as in industrial applications.

Referring to the resistance coupling in Fig. 130, to change to an impedance coupling, simply substitute reactors for the resistors. As actually employed, however, the connections are changed to meet the various requirements. In the diagram, the condenser is unessential so far as the coupling is concerned, but it prevents positive potential from reaching grid g_2. The voltages acting in the plate circuit of the first tube are coupled to grid g_2 of the second tube by the resistance r which is common to both circuits, the condenser offering a path of low impedance to alternating

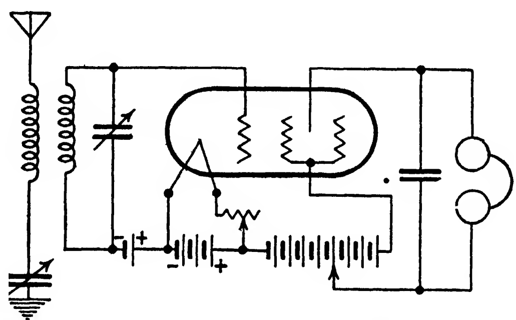


FIG. 133.—Detector-amplifier circuit employing four-electrode tube.

and variable voltages to grid g_2. Resistor r' permits electrons to leak from grid g_2. The resistance coupling is rather inefficient due to the energy converted into heat in resistor r, but it will amplify uniformly over a wide band of frequencies and, therefore, is used extensively in television transmission and reception.

Tubes, condensers and transformers are shielded with metal, and transformers set at right angles to each other, to prevent interference between them.

Many circuit combinations are possible with four- and five-electrode tubes, an example being shown in Fig. 133.

83. Oscillators.—A simple example is that of the inductive feed-back type in Fig. 134. When switch s is closed a current flows through coil b, thereby inducing a voltage in coil a which tends to charge the condenser and also place a negative potential on the grid. This tends to block the flow of current in the plate circuit. Then the condenser begins to discharge through coil a,

thus reversing the direction of the current therein which keeps on flowing on its own momentum after the condenser is discharged and tends to charge the condenser in the opposite direction. This reduces the negative grid potential and changes it to positive, resulting in a further flow of current through coil *b*, thus giving a kick to the electricity in the tuned oscillating circuit of which coil *a* and the condenser are the main components, the general action being analogous to the power-driven escapement, balance wheel, and hairspring of a clock or watch, as described in Art. 48. One of the first types of oscillator to appear was that of "feedback" Armstrong, famous as the inventor of the superheterodyne.

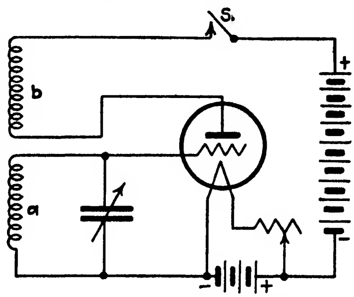


FIG. 134.—A standard oscillator circuit.

If coil *a* is inductively coupled with an antenna circuit, electromagnetic waves will be radiated into space therefrom, as shown in Armstrong's patent, and if a telephone transmitter or microphone is suitably employed to modulate the waves by means of

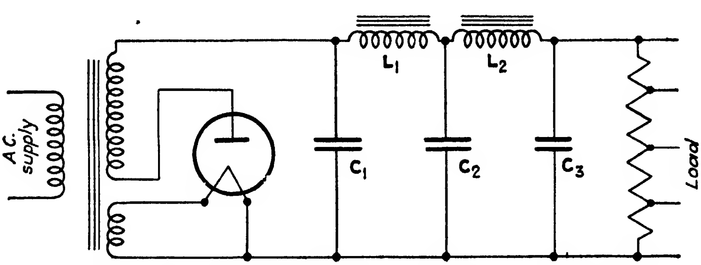


FIG. 135.—Rectifier and filter circuit. Also called "B eliminator."

the voice, the voice will be heard in radio receivers. Enormous water-cooled power tubes are employed for the purpose in radiobroadcasting stations.

84. Changing Alternating Current into Uniform Direct Current.—This is accomplished through rectification and filtration by means of a rectifier tube and a system of reactors and condensers, as in Fig. 135, gaseous-discharge tubes usually being employed to change the alternating current into pulsating direct current, after which the ripples are smoothed out by the filters.

The chief purpose of condenser C_1 is in effect to increase the available output voltage, this being the first filter. The second filter C_2-L_1 smooths out the ripples, while the third filter C_3-L_2 usually is added in broadcast receivers to eliminate substantially all of the hum that otherwise would result. The maximum filtering action for a given amount of capacitance is obtained when $C_2 = C_3$.

The resistor or load usually is tapped as shown to form a voltage divider for the various circuits in broadcast receivers as sources of energy supplanting the "B" battery shown in previous circuits.

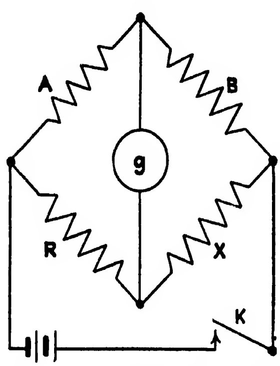


FIG. 136.—Simple Wheatstone-bridge circuit.

85. The Wheatstone Bridge.—Various forms of this circuit (Fig. 136) are used with electronic tubes in various manners, especially where one effect is to be compared with another or where they are to be balanced. It is the well-known circuit used in comparing the resistance, self-inductance or capacitance of a circuit or device with a standard.

Assuming that the resistances A and B are equal, when the galvanometer g does not indicate at all with the key k depressed, the unknown resistance X is equal to the standard or known resistance R. In any case, $A \div B = R \div X$. Hence, with A, B, and R adjustable, the resistance X may be found over a very wide range of resistances.

CHAPTER XII

ELECTRONIC LAMPS

All gaseous discharges or arcs are light sources due to the continual recombinations of electrons with positive ions which occur simultaneously with the ionization of the gas as a whole when the lamps or tubes are in operation. In open arcs the type of gas and its pressure cannot be controlled, but by first removing the air from a bulb and then permitting any desired kind of gas or mixture of gases to move in, both the type of gas and the pressure may be controlled. This is the basis of electron-tube lighting. While the terms "lamp" and "tube" appear generally to be used indiscriminately, the term "lamp" herein is applied only to cases where a gaseous discharge is made to take place within a sealed enclosure or envelope exclusively as a source of light. It was shown in Art. 52 that there is a glow on the cathode and also a positive column of light in such electronic sources of light, the latter predominating in long lamps. In this chapter the term "glow lamp" will refer to those lamps wherein the electrodes are relatively close together and wherein the cathode glow is the light source, the positive column being absent, while the term "gaseous-discharge lamp" will refer to relatively long lamps, with their operating electrodes more widely separated and wherein the light from the positive column mostly is employed, but the line between the two general classes cannot be sharply drawn because each merges into the other. Further details are given in connection with gaseous-discharge tubes in Chap. XIII. The open arc is briefly discussed because it is the original form of all arc lamps.

86. Open Arcs.—The most common form of arc is the open arc consisting of a stream of air ions and a stream of electrons simultaneously flowing in opposite directions between electrodes. Generally it is produced for illuminating purposes by bringing together two carbon electrodes, when the heat developed at the imperfect contact between them vaporizes some of the electrode material, and as the electrodes are separated (generally

by an electromagnet) there results a high arc temperature which, with the accompanying bombardment of the respective electrodes by electrons and ions, further increases the ionization, thus increasing the current strength (for given average speeds at constant voltage) and, therefore, decreasing the resistance between the electrodes. Thus a negative resistance results and means must be provided in all arc lamps to prevent ionization from increasing beyond predetermined limits. Hence ballast resistors are connected in series with arcs on constant-voltage direct-current circuits, while ballast reactors similarly are employed for alternating-current lamps.

The resistances of both such resistors and reactor coils convert electrical energy into heat, thereby reducing the overall efficiencies of the lamps, and the reactors cause a reduction in the power factor (ratio of the actual arc current to the total current including that which magnetizes the reactor).

87. Starting the Arcs.—Although not used to any great extent except as a useful source of ultra-violet and infra-red radiation, the open arc is exceptional in that one or both of its electrodes can be moved so that the distance between them may be varied and ionization produced at the normal operating voltage as described above. But it is possible to set the electrodes at their normal operating separation, with the normal operating voltage impressed across them, and then temporarily impress a much higher voltage upon them to ionize the gas and start the arc or discharge. This ionizing, ignition, or striking voltage may be obtained by causing a current to magnetize an iron-cored inductance coil or reactor and then suddenly interrupting the circuit with a make-and-break switch (Fig. 137) or, if desired, it may be obtained with equipment of the general type used in automobile ignition. This is known as probe starting. In this manner short-circuits occur in lighting systems in laboratories where high-voltage, high-frequency currents jump across the air gaps at outlets in going to and from the ground, the lighting-circuit voltage being sufficient to cause the short-circuit when the air becomes ionized.

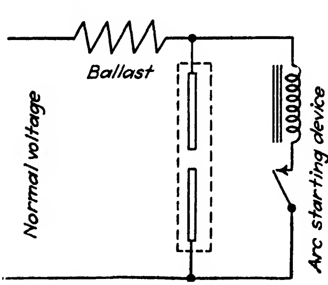


FIG. 137.—One method of starting the arc.

In gaseous-discharge lamps containing gas at low pressure, the electrodes are fixed in position and they may be quite far apart; therefore, relatively high ignition voltages must be employed unless (*a*) the arc is started by temporarily connecting the electrodes within the glass envelope or tube, as by a thin stream of mercury forming one of the electrodes which then travels back to the pool forming said electrode after striking the arc; (*b*) a metallic conducting path outside the glass envelope, as upon its outer surface, brings the potential of one electrode near that of the other electrode to cause ionization by acting through the glass by influence; or (*c*) a third electrode, within the envelope, in a separate ionizing or "keep-alive" circuit, maintains the desired degree of ionization at the cathode so that the arc may be formed when the operating voltage is applied to the usual electrodes. These methods may be, and are, duplicated and extended in alternating-current gaseous-discharge lamps and tubes, some ionization in the immediate region of the electrodes being produced by even relatively low voltages, just as it is produced throughout the entire lamp by high voltages. In some cases auxiliary electrodes are connected in series with resistors having sufficient resistance to maintain only the few milliamperes of current strength required for this local ionization.

88. Classifications of Electronic Lamps.—There are two general classes of electronic lamps besides those mentioned above, namely, the rare-gas class and the mercury-vapor class, the former gases generally being neon, argon, or helium, which are very inert, being but feebly absorbed by glass and other parts of the lamps and not easily combining with impurities in the electrodes, although mixtures of gases have been employed, as of neon and mercury vapor, for the purpose of producing "white light," and carbon dioxide gas has been used for the same purpose since the beginning of the present century, but carbon dioxide has a tendency to be absorbed by sputtered electrode materials (Art. 53).

Electronic lamps may be further subdivided into the cold-cathode and hot-cathode types, the latter being of the filament, heater-cathode, or arc-heated variety.

The ignition or striking voltage is greater in cold-cathode lamps than in hot-cathode lamps. When the applied voltage has been reduced until the lamp is extinguished, it must be increased considerably before the lamp will function again.

Thus there are three critical voltages in an electronic lamp, namely, the ignition voltage, the extinguishing voltage, and the zero voltage (the last being important in alternating-current operation), each of which is smaller than the one preceding it.

It follows that, when the voltage increases from zero, the lamp will not operate until the ignition voltage is attained; then, as the voltage is reduced, the lamp remains lighted until the voltage has fallen to its extinguishing value, after which there is a period of darkness until the voltage has fallen to zero, reversed, and increased to its ignition value again. As a result, an alternating-current neon lamp is lighted only during a portion of each half-cycle, thus producing strange optical illusions and eye strain unless the frequency is high. The operation of the mercury-vapor lamp on half-wave rectification also produces similar effects. This phenomenon also may occur with pulsating unidirectional currents but not with continuous currents.

The ignition voltage and the actinic or photographic properties of the lamp are dependent upon the nature of the gas employed. A neon lamp has a low ignition voltage and its light readily affects photographic plates. Therefore it is the gas most commonly used.

The greater part of the voltage is used up close to the cathode, that is, the greater part of the work done in moving a given quantity of electricity is done at this place. The nature and pressure of the gas, as well as the area of the cathode, determine the impedance of the lamp. During operation, electrons are most abundant at the anode and positive ions predominate at the cathode, while at some intermediate point they are present in about equal numbers.

89. Glow Lamps.—All gaseous-discharge lamps have resistances in series whether or not they are concealed. In a common type of the neon glow lamp containing two nickel plates mounted with their surfaces parallel and separated about 1/8 in. apart, when a voltage of about 200 v is impressed upon the plates, it will be noticed that the cathode is covered by an orange red glow and close examination will show that it is separated from the cathode by a narrow dark space, the intensity of the light falling away on the far side of the glow. This is the cathode layer or cathode glow. Such lamps are prevented from discharging further by the resistance in series with them.

Refined applications of neon and other glow lamps are found in sound-on-film recording, as in sound pictures, and in television receivers, since the intensity of their emitted light varies with the current strength and they may be lighted and extinguished, or otherwise varied, a hundred thousand times a second. Hence the light may be modulated by the voice or other sounds (Fig. 138) much as radio waves are modulated. In general, such glow lamps contain the proper electrodes and rarefied gases at a pressure sufficient to concentrate the glow on the cathode.

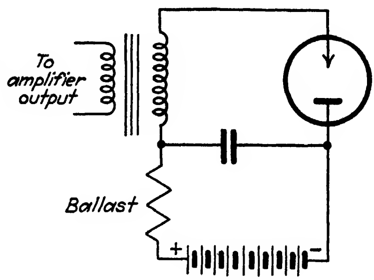


FIG. 138.—Typical circuit of cold-cathode glow lamp for sound-on-film recording and television reception. The modulation takes place through the branch including the condenser.

Earlier glow lamps for monochromatic or single-color television are cooled by radiation only; the intensity of their glow, therefore, is limited by a current capacity of only about 50 ma., but this has been increased to 500 ma. by the introduction of water cooling, giving a very bright glow on the cathode. In some television glow lamps the glow discharge is confined to a flat surface by mica shielding so that the intensity of the glow, rather than its volume, will change with voltage.

For monochromatic television and for the red component in color television neon is used as the discharge gas. For the blue and green components argon is employed. Color filters are used with the lamps for color work.

In one form of glow lamp the entire wall, with the exception of a small window, is covered with a metallic coating which acts as the anode. The plate inside the tube is the cathode, having an area of 1 sq. in.

Glow lamps also serve as sources of visible radiation of definite frequencies for the carrying out of photochemical reactions, as a means of supplying and checking stroboscopically (explained below) audible frequencies for conductivity and dielectric constant measurements, and as a means of indicating light intensities when used with photoelectric cells.

It is characteristic of glow lamps that their resistance increases as they age. But the reduced current in the ballast resistor

causes a reduction in the voltage drop therein, thus tending to keep the current strength constant.

The little 0.5- and 1-w glow lamps which fit standard sockets and operate on either direct or alternating current at extremely small cost, each of which is provided with a resistance of several thousand ohms, mounted in the base, have a great many uses in homes, hotels, factories, hospitals, laboratories, and so forth, as night lamps for bathrooms, nurseries, sick rooms and cellar stairs; for illuminating house numbers; as pilots or guides; as signals; as illuminants for stroboscopes since the glow immediately vanishes below a critical or extinguishing voltage; for flashing free from lag, as oscillators; as polarity indicators on direct-current circuits, since only the negative electrode glows and thus also indicates whether the voltage of a circuit is direct or alternating, and so forth. On alternating current the glow is produced only during a portion of each half cycle and at the two electrodes, alternately and periodically, which are 1/16 in. apart. These little lamps have a rated life of 3,000 hours.

Such a lamp will flash intermittently if connected in a direct-current circuit of sufficient voltage with a series resistor and a shunt condenser, the frequency of the flashes being governed by the values of the resistance and capacitance. The condenser charges through the resistor until its voltage is equal to the striking or ignition voltage of the lamp, at which time the condenser discharges through the lamp and the cycle starts again.

In one line of glow lamps the units consist of short metal-coated glass tubes which are lacquered, a condenser effect being produced between the metal coatings which act as the plates, with the glass and gas as the dielectric. Because of the relatively small distance between the plates, the gas is broken down much as a weak dielectric is broken down, by a relatively low potential. This principle is incorporated in gaseous-discharge lamps wherein electrodes on the outside of the glass bring the potential of one electrode near that of the opposite electrode to cause the ionization of the gas.

Neon glow lamps 1/2 in. in diameter, with a 1-in. separation of electrodes, are used as ground detectors on a delta (three-phase) electric-power distribution system by suspending them by wires, with insulators (which act as dielectrics of condensers) between them and the lines, and the opposite electrodes of all three are connected together and to the ground. If one of the lamps is

extinguished, there is a ground on the corresponding phase or the lamp is defective. The lamps are kept in a small darkened building with a peep hole, so that they may be looked at now and then.

Another use of electronic lamps is the marking of high-tension lines in the proximity to air fields by neon lamps a foot long hanging freely from, and in contact with, one wire, the other lamp electrode being fitted with a number of sharp points discharging to the air. These are sufficiently bright to warn aircraft at night.

90. Stroboscopes.—One form of spark-producing device consists of a type of inductance coil or reactor in series with a battery and a pair of contacts which, if placed together and then pulled apart, will have a bright spark between them when the circuit is interrupted. If a rotating toothed wheel and a flat spring replacing the respective contacts are so arranged as to close the circuit when a tooth strikes the spring and immediately thereafter break the circuit when the tooth passes in a darkened room, the wheel appears to stand still or to be "stopped."

Instead of depending upon the spark as a light source, a neon lamp may be lighted and extinguished each time the circuit is completed and interrupted. This principle is employed in a simple portable instrument for studying the behavior of rapidly moving machine parts, whether rotating, oscillating, or vibrating, so long as the motion is cyclic, and moving parts can be made to appear stationary at any desired position in the cycle of operation. The flashing lamp is controlled either by a breakerhead which is driven directly from the mechanism under observation, or by a governed motor unit. By adjustments, the movements also can be observed at greatly reduced speeds, as in slow-motion pictures.

The briefer and more intense the light flash of the neon lamp the more pronounced is the illusion. In this manner the speeds of inaccessible parts of machines may be determined; the oscillations of synchronous motors and other machines may be measured; commutators may be inspected when running at full speed, and so forth. A stroboscopic disk and two neon glow lamps are used in the measurement of corona loss.

Stroboscopic action is that which makes wheels appear to stand still or to turn backwards in motion pictures because the shutter of the camera interrupts the light to the film at a definite rate. If a wheel is turning at such a speed that its spokes take

each other's places during the same time interval, the wheel appears to be at rest, although its rim may be seen as rotating.

In a factory, for example, lighted by 25-c, hot-cathode gaseous-discharge lamps employing half-wave rectification, it might be impossible to tell which way wheels were turning, unless each had a white mark on its rim, and other effects would be noted. When the frequency is increased, however, this action is not so objectionable. It disappears entirely when direct current is employed.

By means of a new timer developed by the Bell Telephone Laboratories a jeweler can regulate a watch in ten minutes, instead of requiring ten days for the purpose, and can quickly diagnose any trouble. In New York City there is a constant-frequency generator delivering an alternating current of 100 cycles per second, accurate to one part in ten million, which is furnished jewelers by the telephone company. Within the timer is a synchronous electric clock motor driven by the 100-cycle current and a flashing lamp. When the balance wheel of the watch has the same speed as the motor, the former appears to stand still.

91. Stroboscopic Photography.—A synchronous motor, for example, may be running in synchronism without a load and again when loaded, but during the transition between these two steady operating conditions there is an oscillation which can be observed by the eye but which cannot be analyzed because it happens so quickly. Then it is desirable to make a photographic record that may be analyzed at leisure.

Problems of this nature led to the development by Edgerton and Germeshausen of a method of taking motion pictures on a continuously moving film without the use of a shutter at the rate of 480 pictures a second, and they also reported successful photographs at 4,200 exposures a second, using mercury-vapor lamps for producing the light. This is accomplished by means of a special circuit containing a condenser which is charged and then suddenly discharged through the lamp by purely electronic means, the duration of the flash usually being less than 10 millionths of a second. The film was driven by a synchronous motor at the speed 15 ft. per sec. Four one-foot stroboscopic lamps requiring 3 kw of power are needed to run the outfit when taking motion pictures at the rate of 480 per sec. Water running from a faucet appears frozen solid in one of these single photographs, while the various stages of rapid actions, like the breaking

of a lamp bulb with a golf club, may be studied at leisure, the latter showing a crack developing along the bulb and so on until it has been shattered into tiny bits.

92. Differences between Visual Light Signals, Scenic Effects, and Illumination.—There is a vast difference in the qualities and intensities of light required for signals, advertising signs, color effects, and so forth, and the light required for illuminating the surfaces of objects to be studied, worked on, inspected, and read. Lamps for the latter purpose are the real illuminants. Thus a flash from a pocket flasher a mile away may serve as a satisfactory prearranged signal at night, or a reflected flash of sunlight might answer the purpose in the daytime, yet the light from the flashlight a mile away would be useless as a source of light by which to read and the reflected sunlight might be too intense for the same purpose. Who would care to read these pages if illuminated by blood-red light? Yet colored signs and the rainbow may be pleasing to the eye.

Mercury-vapor and sodium lamps are efficient light sources, but because of their colors and the way human faces appear when illuminated by them, they are not apt to become popular in homes, offices, and public buildings. Since the mercury-vapor lamp emits no red rays, its light has a ghastly greenish-blue color, making the veins in the hand, for example, stand out like little purple streams. This is due to fluorescence of the living tissue in the ultra-violet.

The "artificial daylight" color-matching carbon dioxide lamp, whose light very closely approximates the daylight of the blue quality of the north daylight, was developed by Moore about 30 years ago.

93. Gaseous-discharge Lamps.—The familiar cold-cathode lamps in general use in advertising signs require thousands of volts for starting the ionization and for their operation, from 2,000 to 10,000 v or more being customary, and the lamps must be made long enough to operate on at least 1,000 v for satisfactory efficiency since the voltage drop at the cathode may be of the order of 400 v with its corresponding energy loss which results in a sputtering of the electrode material on to the adjacent glass walls, increasing with temperature, thus limiting the current density at the electrode surface to about 40 ma. per sq. in.

When used in multiple circuits at constant voltage, after the manner of incandescent lamps, series ballast resistors and reactors

must be used with them in the respective direct- and alternating-current circuits, each of which devices may absorb from one-quarter to one-half of the supply voltage, sometimes reducing the overall efficiency rating by as much as 30 per cent, and the reactors make the power factor as low as 40 per cent in alternating-current circuits, these being disadvantages that apparently cannot be avoided in this general type of lamp, although incandescent lamps may be, and are, employed as ballast resistors, and the power factor may be, and is, corrected with static condensers, or capacitors, permittors, and so forth, which absorb the energy discharged from the reactors during each half-cycle and then pass the energy back to the reactors during each following half-cycle.

Although these lamps principally are used for advertising signs, they are coming into use as high-intensity beacons and

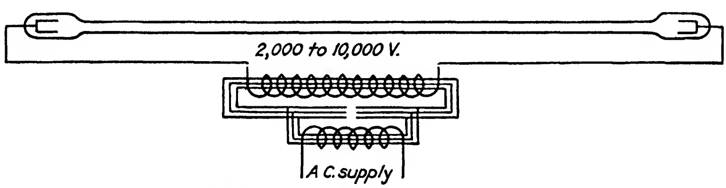


FIG. 139.—Alternating-current, high-voltage, low-current, cold-electrode, gaseous-discharge lamp generally used for sign-lighting work. The magnetic-leakage feature of the transformer makes it possible to use the secondary as the ballast reactor. Power factor 40 per cent. (*After Mailey.*)

flood-lighting sources, and in art galleries, commercial interiors, particularly theaters, lobbies, shops, and so forth.

The mercury-vapor lamp inherently is of the direct-current class, while the neon lamp inherently is of the alternating-current class.

Objections to the high-voltage type of lamp are its necessary high-voltage insulation, safety hazard, and the utilization of the long and fragile tubular units. A typical alternating-current, cold-cathode, gaseous-discharge lamp and its circuit are shown in Fig. 139.

94. Hot-cathode Lamps.—These were developed to provide a high-intensity gaseous-discharge source of lower voltage for various purposes, based on the Edison effect in some cases and on the principle of the arc in others. A characteristic of the hot-cathode lamp is that time is required for it to start. Both filaments and cathode heaters of various forms are employed, the oxide-type cathode being extensively used.

A disadvantage of the hot-cathode lamp is that sputtering is increased, thus tending to blacken the glass and absorb some gas, with a reduction in pressure and increase in impedance in small lamps, whereas the cold-cathode lamp gives stable and constant illumination. An advantage, however, is that the ignition voltage may be reduced, thus also decreasing the resistance of the lamp which is largely confined to the cathode.

Electrons from the hot cathode collide with the molecules of the gas, thereby producing ionization. The positive ions thus produced tend to neutralize the space charge and thus reduce the voltage drop which, for an oxide filament in a small lamp, is about 15 v for mercury vapor and about 30 v for neon gas.

According to Langmuir, free electrons and positive ions are drawn into the positively charged region until the space charge is reduced to zero, resulting in a division into electrode layers and the positive column, the electrons set free in the positive column by fast electrons from the electrode layers having considerable random velocity, and a random current of electrons adding itself to the drift or field current. The walls of the tube also become negatively charged; the discharge, therefore, is a rather complex phenomenon.

In long gaseous-discharge lamps, calcium oxide fused into the surface of a platinum electrode permits greatly increased current strength for a given voltage drop and temperature, as also does barium oxide on nickel surfaces, the voltage drop being about one-tenth of that of the corresponding cold and unactivated electrode. The prepared electrodes are heated to a temperature of about 900 deg C, being either arc- or internally heated, the internal heater sometimes being connected directly in series with the gaseous discharge, thus also serving as the ballast resistor on direct-current circuits, at least.

All such heaters must be heated to substantially the normal operating temperature before the discharge takes place, special electrodes being required in the larger sizes. In order to start these low-voltage lamps, ignition voltages of thousands of volts are momentarily applied to long tubes.

The familiar form of the mercury-vapor lamp consists essentially of a glass tube (Fig. 140), several feet in length, containing mercury vapor and a pool of metallic mercury which forms the cathode. At the opposite end of the tube is an iron anode.

When cool, the resistance between the cathode and the mercury vapor is very high. One method of starting the lamp is simply to tilt it so that a thin stream of mercury connects the two electrodes and then allowing the lamp to return to its initial or normal

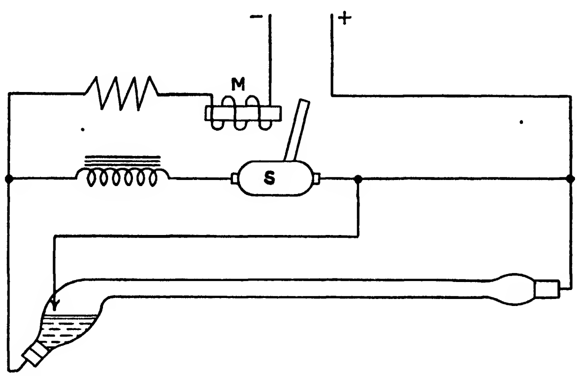


FIG. 140.—Principle of mercury-vapor lamp and starter.

operating position, thus breaking the circuit sufficiently to form an arc. In other cases a high voltage from an inductance coil or reactor causes ionization. This is accomplished through the action of a mercury switch S operated by an electromagnet M,

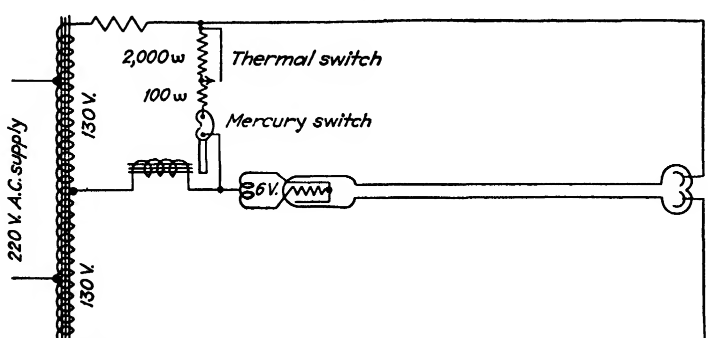


FIG. 141.—Alternating-current, low-voltage, probe-starting, internally heated cathode, rectifier-type, gaseous-discharge lamp containing mercury vapor, neon, or other gases. (*After Mailey.*)

the current first flowing through M, the resistor, the reactor and the shifter. Before the electromagnet has time to operate, however, magnetic energy has been stored in the reactor, so that when the electromagnet does operate to open the switch, this

energy is discharged at high voltage between the mercury-pool cathode and the auxiliary starting anode near it.

The mercury-pool cathode will withstand overloads and instantaneous current demands that an oxide cathode cannot carry. It is a type between the cold- and internally-heated cathodes and is the basis of many of the tubes described in this volume.

In the circuit in Fig. 141, each terminal of the autotransformer alternately and periodically is positive and negative; the alternating-current gaseous-discharge lamp operates therefore on double rectification, the current flowing first to one of its anodes and then to the other. In starting, a current of less than 1 amp. flows from

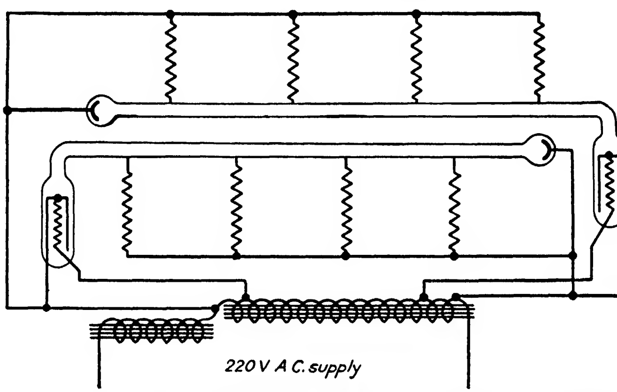


FIG. 142.—Alternating-current, low-voltage, probe-starting, internally heated cathode, half-wave rectifier, gaseous-discharge lamp with local ionizing electrodes. (*After Mailey.*)

the mid-tap of the autotransformer through the ballast reactor which then attracts the iron armature of the mercury switch, causing it to open the evacuated mercury switch. The high-voltage discharge of the reactor ionizes the gas.

By carrying the anode voltage to various points along the tube, as in Fig. 142, ionization is enhanced. Using the reverse of this principle, gaseous-discharge lamps or tubes may be, and have been, used as voltage dividers.

95. Efficiencies of Gaseous-discharge Lamps.—The overall efficiency of a lamp is rated in terms of the number of lumens emitted per watt of power consumed by the entire lamp, ballast and all. The lumen is equal to 12.57 mean spherical candles; therefore, a lamp emitting 12.57 lumens per w would be rated as 1 candle per w. The actual average efficiency of the best incan-

descent lamp is less than 10 per cent, that is, the ratio of the light energy emitted to the electric-energy input is less than 10 per cent, because so much electrical energy is converted into heat. The ideal light is cold light.

The overall efficiencies of lamps increase with power input. Hence all should be compared at the same power input in watts. Taking the 500-w tungsten-filament incandescent lamp as a basis, it has been found that the low-pressure mercury arc and the neon lamp with inductive ballast rank with it in overall efficiencies of 17 to 19 lumens per w, the helium lamp with resistance ballast being only about 20 per cent of that of the tungsten-filament lamp. The efficiency of the carbon dioxide lamp is only about 20 per cent of that of the tungsten-filament lamp. The overall efficiency of the neon lamp with resistance ballast is about 75 per cent of that of the same lamp with inductive ballast. This shows that incandescent lamps should be used as ballast resistances for gaseous-discharge lamps wherever practicable, since the overall efficiencies of the combinations thereby may be increased. Incandescent lamps also may be obtained in tubular form.

96. Grid-glow Lamps.—In modulating the light from a glow lamp, distortion occurs owing to the fact that when the voltage is reduced to the extinguishing voltage the lamp current suddenly falls to zero instead of falling off gradually with the voltage, and then the voltage must increase beyond the extinguishing value to the ignition value before a current again will flow.

To eliminate this form of distortion, a third electrode was introduced into the standard two-electrode glow lamp, the function of which is to make the ignition voltage equal to the extinguishing voltage by allowing a very small unmodulated ionizing current to flow at all times. This ionizing current is independent of the modulating current between the two normal electrodes, and causes the gas to remain ionized with a faint cathode glow even when the normal lamp current is reduced to zero, just as there are a plate current and a separate grid current in a vacuum tube. This grid, however, has substantially no control over the discharge once it is started, a characteristic of gaseous-discharge lamps and tubes very different from those in vacuum tubes. A typical circuit is shown in Fig. 143.

Ionizing electrodes and control grids are found in many types of lamps and tubes. Even the triode of DeForest contained some gas which could not be removed with the earlier vacuum pumps.

97. Color Requirements.—Daylight tungsten-filament lamps at reasonable prices have been on the market for years, yet they are only 2 per cent of all lamps sold. Warm colors seem to be preferred in showrooms and windows, except on surfaces like chromium, nickel, and silver.

An advantage in neon and mercury lamps is that full efficiency is obtained for their colors, whereas the red and green light obtained from incandescent lamps by coloring materials either on or in the bulb absorb 90 per cent of the light and the absorption for yellow is about 30 per cent. Hence the former lamps have the advantage as decorative mediums. Nevertheless, a better white light can be obtained from a combination of a mercury lamp and one or more incandescent lamps than can be obtained with mercury and neon lamps combined.

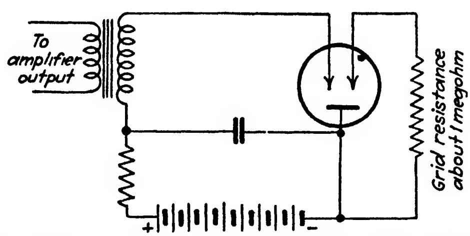


FIG. 143.—Three-element or grid-glow lamp as used in sound-on-film recording. (*After Braman.*) See also Fig. 138.

98. Lamps of the Future.—The advent of the tungsten-filament incandescent lamp, with an efficiency substantially three times that of the carbon-filament lamp, gave consumers the option of using three times as much light for the same money or the same amount of light for one-third of what they previously paid for it, over and above the minimum charge.

Carbon and tungsten are two of the relatively few elementary substances that pass into the gaseous state without melting, or else simultaneously melt and boil without any evidence of melting. Tungsten filaments cannot be operated at higher temperatures than at present because of the evaporation of the tungsten and the consequent blackening of the bulb.

The success of the gaseous-discharge lamps in the advertising-sign field, some of which operate with long life and high overall efficiency, and which may be made for current ratings of 1 to 20 amp. or more, has caused many investigators to believe that the filament may be entirely superseded by a gaseous discharge,

thus giving consumers a further benefit similar to that obtained with the advent of the tungsten-filament lamp, so that a number of men in the industry are seriously concerned with the position of the public utilities in case higher efficiencies are obtained since considerably more than half of the money spent for electrical energy is for electric lighting.

In what follows, the relative efficiencies of modern incandescent and gaseous-discharge lamps in the smaller sizes should be borne in mind, and that as an illuminant some of these lamps are less efficient than incandescent lamps of equal wattages, and also that some of the claims which follow have not necessarily been universally accepted. Furthermore, the lamps are only in the experimental or trial stages of development.

Some of those experienced in the manufacture and installation of gaseous-discharge lamps, as stated in two articles in *Electrical World* in 1932, one by R. D. Mailey (July 9) and one by W. Harrison (November 19), to whom the author is indebted for much information used in this chapter, appear to take the view that, in order to be satisfactorily efficient, gaseous-discharge lamps should be made in units much larger than ordinary incandescent lamps and preferably may be of the built-in variety, installed completely with their auxiliary apparatus.

Others have stated that the lack of flexibility of the gaseous units and their requirements of special voltages and mechanical forms have so far limited their applications as general commercial illuminants, and have worked on developments along the line of the individual unit which can be screwed into an ordinary lamp socket.

Development probably will proceed along both of these two general lines. Practically all the development work on gaseous-discharge lamps as general illuminants is being done on lamps designed to operate at 220 v or greater. This development has centered largely around the lamp electrodes.

The yellow sodium-vapor lamp, developed by Pirini, is very promising from an efficiency standpoint, having an overall efficiency of 50 to 70 lumens per w, in 300- to 500-w sizes, but the human features appear even worse under its otherwise pleasing warm yellow illumination than under that of the mercury-vapor lamp and color discrimination under its radiation is almost impossible. Furthermore, its cost, except in 100-w sizes, may offset its efficiency because of the necessity of using in its con-

struction a special glass that will resist the attack of the very active sodium vapor, and to the further fact that the vapor must be prevented from condensing by "thermos-bottle" insulating the lamp with a second bulb or tube from which the air is exhausted.

The sodium lamp has the customary series ballast, but no other auxiliaries, and is self-starting on commercial circuits. Nevertheless, it requires about 10 min. to come up to full brilliance and it must cool for a similar period after it has been switched off before it will again begin to emit light. Its efficiency and starting and cooling time decrease with size.

One field where the sodium-vapor lamp apparently can be used to good advantage is in street and similar lighting. An experimental highway installation of 100-w lamps has been made

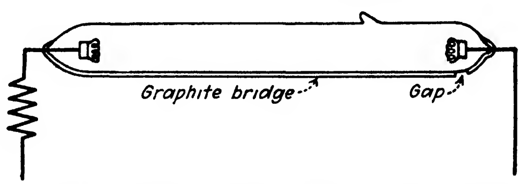


FIG. 144.—The high-resistance circuit painted on the outside of the glass brings the full operating voltage up to the gap near one cathode, thus facilitating ionization and quick starting.

in Holland. There also is a half-mile experimental street installation in New York state.

The Meyers lamp, developed primarily as a source for television, employs a quartz tube of special shape and containing a small quantity of mercury. As reported in *Electronics*, "Mr. Meyers made this tube glow in the focus of an induction coil, as a 3,000 candle-power lamp." It was claimed that 24 candles (about 300 lumens) per watt could be obtained in the larger sizes. There appears to be considerable auxiliary apparatus required with the lamp.

As reported, one form of the Spanner-Germer-Doring lamp consists of a glass tube about 5 in. long with a barium-oxide cathode at each end (Fig. 144) and filled with a mixture of neon, argon, and mercury vapors at very low pressure, but with no mercury or other liquid therein. A high-resistance conducting strip of graphite, painted on the outside of the glass tube and ending in a gap near one of the cathodes, brings the full operating voltage to bear upon a small portion of the gas in starting, after the manner described in Art. 94.

As exhibited in America, one of these lamps operated on a 110-v lighting circuit in series with a 55-v, 500-w incandescent lamp which also served as a ballast resistor, both having the customary screw-socket bases, the two sockets being wired together as a unit. While both lamps operated instantly when switched on there was considerable overvoltage on the incandescent lamp, which gradually decreased to normal operating brilliance in about three minutes, but after being switched off, they could not be restarted until after about a four-minute wait, as reported in *Electrical World.*

In this connection, the first combination of mercury-vapor and incandescent lamps for the purpose of securing white light was installed in the editorial offices of the New York *World* early in the present century.

The lamps can be made not only in the intricate designs required to produce the effect of luminous handwriting, but also in the form of tubes curved back on themselves to produce a "bulb," as shown in Fig. 145, for standard screw-socket mounting. They also must have a ballast resistor or reactor of some kind. It is stated that larger and longer lamps used in Europe employ current strengths of 3 to 5 amp., and it is claimed that these new lamps are from three to five times more efficient than the best filament-type incandescent lamps, but whether or not this claim is made for equal wattages is not known at this writing.

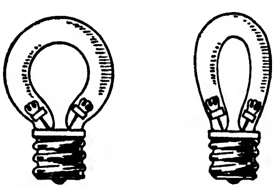


FIG. 145.—Adapting tubular gaseous-discharge lamps to standard lamp bases.

What seems to be required for general illumination is a 110-v lamp of moderate first cost and available in a range of sizes which includes low wattages, and of reasonably acceptable color, that will operate steadily on either direct or alternating currents, at frequencies of 60 c or more and at efficiencies higher than those of incandescent lamps of equal wattage and preferably with longer life, which will not lose its output efficiency either upon warming up or with reasonable age; it should be possible to switch such a lamp on and off as often as may be required without any waits or delays of any kind, just as with incandescent lamps and with no more thought of attention to them, remembering that the typical lamp of to-day averages about 60 w.

It is possible to mix mercury vapor with any desired element to produce light of almost any color. A mixture of the vapors of mercury, zinc, and cadmium gives a light much like daylight; cadmium a bluish light tinged with a little red, and there are combinations possible with these elements and neon, argon, and helium; the opinion has been expressed, however, that the green mercury-vapor or the red neon lamps, either singly or in combination, will be the primary types of efficient lamps for general illumination by gaseous conduction in the future, since these, with the yellow sodium, are the only gases that have been made to generate light in reasonable efficiencies, and it is probable that two or three color lamps will be grouped together in a single source area for the approximation of white light.

One recent advance in miniature Mazda lamps has been the inclusion of neon gas therein, so that when the filament fails on any lamp in the string of eight in series, the full voltage acting on the neon in the single lamp causes it to glow and thus indicate where the trouble is.

CHAPTER XIII

GASEOUS-DISCHARGE TUBES

Glow tubes operate on the same general principle as glow lamps. As compared with vacuum tubes, glow tubes and gaseous-discharge tubes in general are current devices having much lower impedance. The term "tube" herein is confined to gaseous-discharge or conduction devices, as distinguished from lamps, whose glow, while desirable or necessary in many cases, is not necessarily visible in others, as when the vapor is confined in a steel tank. To this general class belong the high-power tubes used as power rectifiers and inverters, as well as the smaller glow tubes which also may serve as lamps while simultaneously performing their functions as relays, rectifiers, inverters, and so forth. Thus, while the term "lamp" always refers to a source of light, the term "tube" herein always refers to a device serving some other purpose in an electric circuit. Fundamentally, there is very little difference between the various forms of tubes and the corresponding forms of lamps, although they are used for entirely different purposes. There are cold- and hot-cathode, two-, three-, and multi-electrode tubes, as in the lamp classifications, the smaller three-electrode tubes being called grid-glow tubes. The Poulson arc is described first for the same reason that the open arc first was discussed in the preceding chapter.

99. Negative Resistance and Oscillations.—It has been stated in Art. 58 that negative resistance and tube capacity or capacitance cause circuits including vacuum tubes to go into oscillation unless precautions are taken to prevent it. All arcs contain negative resistance. Poulson employed the arc to generate high-frequency currents for radio transmission purposes.

Negative resistance is the phenomenon whereby the voltage drop decreases when the current strength increases, and *vice versa*, which effect is different from that in a metal conductor

wherein the current strength and the voltage drop increase and decrease together (see Art. 109).

A schematic circuit of the Poulson-arc generator is shown in Fig. 146, wherein a direct-current generator is employed as the source of electrical energy. The resistor *r* is the usual ballast resistance found in arc lamps to prevent the short-circuit of the system as the arc resistance decreases. The reactor *L* prevents high-frequency currents from flowing in the input side of the circuit. The oscillating output side of the circuit includes the arc, the condenser, and the primary coil of the antenna coupling.

When the current begins to flow in the arc a portion of it is diverted therefrom as a charging current in the condenser, thus momentarily reducing the strength of the current in the

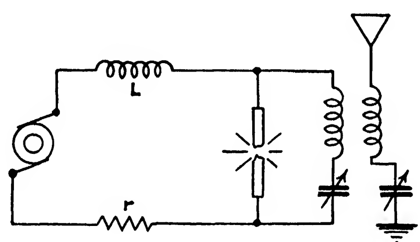


FIG. 146.—Circuit of Poulson-arc high-frequency generator.

arc. This causes the arc voltage momentarily to be increased, which effect, in turn, causes a further charging of the condenser until the voltage across the condenser is equal to that of the arc. Because of the self-inductance of the antenna-coupling primary, the current in the condenser and the primary keeps flowing on its own momentum after the voltage of the condenser has become equal to that of the arc, thus still further charging the condenser.

Then the condenser begins to discharge through the arc in the reverse direction, the increased current strength through the arc causing a reduction in the arc voltage, which permits the condenser further to discharge, the self-inductance of the antenna-coupling primary keeping the current flowing as it swings in the opposite direction, when the condenser again begins to charge and the cycle is completed.

In the practical application of this principle a slowly rotated carbon cathode is employed. Since the anode must be kept cool, it usually consists of copper which rapidly conducts the

heat to circulating water. The arc takes place in hydrogen or in a gas rich in hydrogen, as in coal gas, and is deionized or extinguished at the completion of each half-cycle or alternation by means of a huge electromagnet (about 10 ft. high for 500 kw), the magnetic field of the electromagnet repelling the arc much

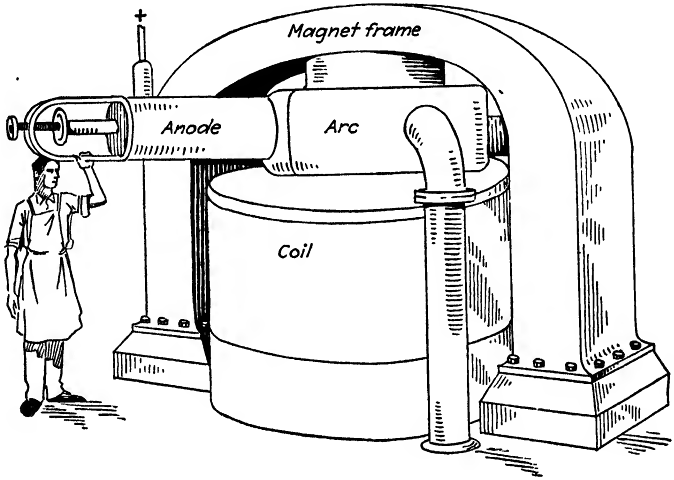


FIG. 147.—General form and relative size of Poulson-arc generator.

as current-carrying wires are repelled in a magnetic field. The positions of the electrodes are shown in Fig. 147. Hence the device appears principally as a large electromagnet. These generators have been made in sizes up to 1,000-kw capacity. The usual wave length is 6,000 m, the frequency being 50 kc per sec.

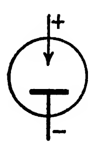


FIG. 148.—Graphical representation of a two-electrode, cold-cathode, gaseous-discharge tube.

100. Two-electrode Tubes.—Figure 148 shows how two-electrode cold-cathode tubes are represented herein. A marked difference between hot-cathode and cold-cathode gaseous-discharge tubes and lamps is that the cathode surfaces in the latter usually are much larger than the anode surfaces. Only a given current strength can be obtained for each square inch of cathode surface with a given tube voltage, that is, the current density (as in milliamperes per square inch) is limited, largely due to the sputtering of the cathode material where the electrons leave it to ionize the gas, whereas the electrons entering a relatively

small anode in the same tube can do so without unduly heating it. This limits the tube current strength to that equal to the product of the current density at the cathode surface and the surface of the cathode, the number of milliamperes of tube current being equal to the product of the permissible number of milliamperes per square inch and the number of square inches of cathode surface.

The cold-cathode (as well as the hot-cathode) gaseous-discharge tubes have a rectifying action when the surface of one electrode is made considerably smaller than that of the other for, if the larger surface becomes the cathode, as the circuit voltage

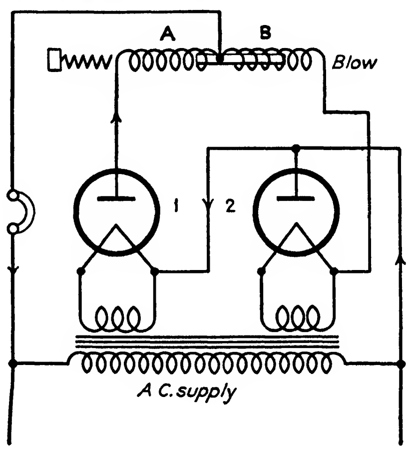


FIG. 149.—Circuit of Syntron electric hammer. The arrows show the direction of the electron current in exciting coil *A*. When the voltage swings in the opposite direction, the electron current flows in coil *B*.

swings to and fro, a larger or stronger current will flow from it than will flow from the smaller electrode when it, in turn, becomes the cathode because in the latter case the product of the current density at the cathode and the cathode surface will be smaller, as shown in Fig. 148. Rectifiers of this general type have been employed in broadcast receivers.

A typical example of the use of rectifier tubes is shown in Fig. 149. This circuit is employed in the operation of the Syntron electric hammer for drilling holes in concrete at high speed and for other purposes, wherein currents in two solenoids alternately and periodically act on a common steel core to pull it to and fro in synchronism with the alternating current in the line. Tungar rectifiers, consisting of argon-filled tubes, are employed to change

the alternating current into pulsating current. When the voltage pulse is negative on the right-hand side of the circuit, the electron current flows through tube 1 and coil *A* and the steel core or plunger hammer is pulled in that direction to compress a spring. On the reverse voltage swing, the electron current flows through coil *B* and the plunger hammer is pulled in that direction as it simultaneously is pushed by the spring, thus causing it to strike a sharp blow—60 times a second on a 60-c circuit.

Figure 150 shows two half-wave rectifiers operating in conjunction with a filter for supplying direct current, as to a radio receiver. Since the mid-tap of the larger transformer secondary always is negative with respect to one or the other of its end wires, the electron current alternately and periodically

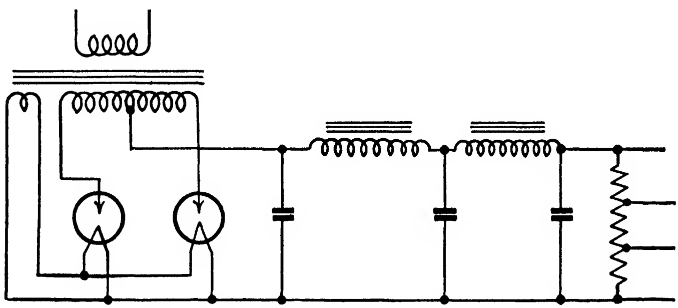


FIG. 150.—Full-wave rectifier and filter.

flows upward, first through one tube and then through the other, to a positive end wire.

Two-electrode tubes, as glow tubes, may be used (besides any necessary ballast) as resistors in direct-current circuits and as "impedors" in alternating-current circuits in special instances. They may be connected in series, in parallel, and in series-parallel by using suitable tubes. They also may be used as voltage-limiting devices, as in parallel with a condenser, discharging when the voltage attains the ignition or striking voltage of the tube, but ceasing to pass current when the extinguishing voltage is reached, since it operates between maximum and minimum voltage limits. In this manner, a condenser, for example, always may be kept charged to a difference of potential which never shall be less than a given minimum in a variable-voltage, direct-current circuit, whereas a resistor would cause the complete discharge of the condenser when the voltage of the circuit fell to zero.

101. Multi-electrode Tubes.—Figure 151 shows the connections of a mercury-arc rectifier, wherein C is the mercury-pool cathode. A and A' are the anodes which function alternately and periodically as the voltage reverses, so that the arc passes first between C and A and on the next half-cycle between C and A'. L and L' are reactors for storing magnetic energy to keep the current going while the voltage is falling to zero, reversing in direction, and increasing to its ignition of striking value in the opposite direction. Consequently, during one half-cycle the conventional or positive current (which is the direction of flow of the positive ions in the tube) is in the circuit shown by arrows 1, 2, 3, and 4, while in the following half-cycle it follows arrows 5, 6, 7, and 8. The electron current, of course, flows in the reverse direction.

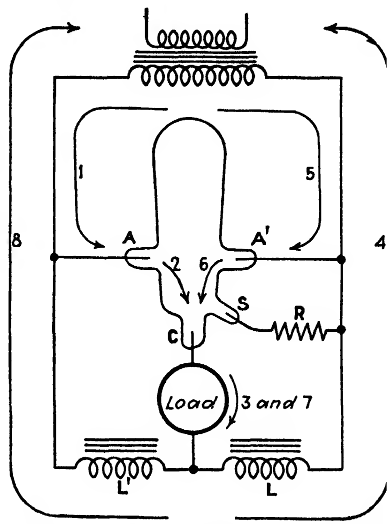


FIG. 151.—Full-wave mercury-arc rectifier. The arrows show the direction of the conventional or positive current, 1, 2, 3, 4 being for one half-cycle and 5, 6, 7, 8 for the following half-cycle.

Thus reactor L is magnetically charged, while the arc represented by arrow 2 is flowing, and as the voltage in that direction falls to what would be its extinguishing value, reactor L discharges its energy, thus keeping the arc going until the arc represented by arrow 6 is formed, the two arcs overlapping and thereby reducing the pulsations of the direct current sufficiently for commercial purposes. Where smoother currents are required, filters must be employed.

This rectifier has been extensively used for charging storage batteries, in operating direct-current arc lamps, and also in place of rotary converters in substations and on trains in traction systems. This type is a full-wave rectifier, as both half-waves are rectified in the same tube, neither being suppressed.

The starting electrode S is connected through resistor R to one side of the circuit. The tube is started by tilting, or it may be started by probe-starting, as in the case of the mercury-vapor

lamp (Art. 94), the arc between C and S causing the ionization of the vapor.

102. Grid-glow Tubes.—The principle of the grid control in glow and gaseous-discharge tubes easily is understood by reference to Fig. 152, recalling that the gas in a tube must be ionized by a very small current before the discharge can occur throughout the entire tube.

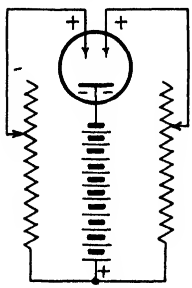


FIG. 152.—Principle of the grid-glow tube.

Both circuits and anodes in Fig. 152 are identical and interchangeable. A very weak current flows in each circuit but there can be no major discharge because of the high resistance in each circuit. If either circuit is opened there still will be a faint glow at the cathode due to the remaining current.

If either of the resistances in Fig. 152 is made small enough so that a major discharge can occur in that circuit, then the positive electrode in series with that resistance will be the anode and the other electrode will be the grid, as in Fig. 153 wherein the ballast resistance may be that of the coil, or coils, of the relay, and which may be of the order of 500 ω or more while the grid resistance will be much greater.

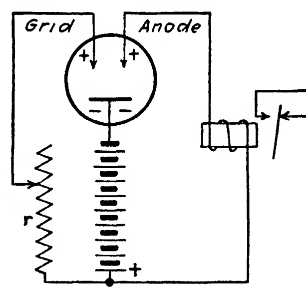


FIG. 153.—Principle of grid control.

Let us suppose that a cold-cathode tube will discharge when the tube voltage, as measured from cathode to anode, is 250 v. Let the anode voltage be 249.8 v without the grid connected. If the grid resistance is of such a value that it will permit enough more current to flow in the tube so that the product of the tube's resistance and the increase in the current strength is 0.2 v, the total voltage across the tube, from cathode to anode and grid, will be increased to 250 v and the tube will discharge. In all cases where the anode and grid are close together it is the sum of the strengths of the anode and grid currents that causes the discharge to occur throughout the tube. When the grid is placed nearer the cathode than is the anode, the effect is substantially the same, except that the grid current does not pass throughout the entire cathode-to-anode distance.

The resistor r in Fig. 153 may be of the electronic type, that is, as a photoelectric cell whose resistance changes when light falls upon its cathode, and so forth, as fully described further on. In this manner a change of resistance in the grid circuit will cause a discharge in the tube through "trigger action" and the current of the discharge will cause the electromagnetic relay or an electronic relay to control another circuit in the customary manner.

The grid-controlled gaseous-discharge or grid-glow tube is itself a relay in that a change in the current strength in one portion will cause an electric current to flow in another circuit of which one portion of the tube is a part. A radio vacuum tube also is a relay in that small changes in the grid potential and current strength produce much greater changes in the strength of the plate current.

In this manner a large amount of power may be held back and then suddenly released by small changes in grid current and voltages, or by exceedingly small changes in power. Thus small tubes may function as very sensitive relays and large tubes likewise may take the places of larger relays, contactors, or magnetic switches in general, in many instances performing their functions better than the electromechanical devices and without the slightest delay, vibration, noise, or any sound of any kind, since they have no moving parts except the electrons and positive ions within them. Even the large tubes may be made very sensitive to operating conditions without any mechanical adjustments of any kind whatever.

The manual, semi-automatic and automatic applications of this principle are very great. Thus the tubes may hold circuits open indefinitely until some change occurs in the grid circuit, as when a switch is closed, or the resistance or capacity varies, as when light strikes a photoelectric cell; a piece of iron is brought near a magnet in the grid circuit; there is surface leakage over an insulator; flames ionize air; the capacity is changed due to the proximity of a person or some inanimate body, and so on. Thus, at the dedication of the electric building of Chicago's 1933 Century of Progress Exposition, a wave of the hand over a grid-glow tube transformed the great hall to a blaze of light and color.

The grid also may be given a negative bias, as in Fig. 154, in which case the discharge will occur only when the negative grid potential is decreased. When the ionizing current is sufficiently

increased, either by making the grid potential more positive or less negative, the necessary ignition or striking voltage between the cathode and the anode becomes decreased. Hence the ignition voltage may be reduced to that of the extinguishing voltage, if desired, or the anode voltage may be maintained at some value between the values of the extinguishing and ignition voltages and the positive grid voltage varied until the discharge occurs.

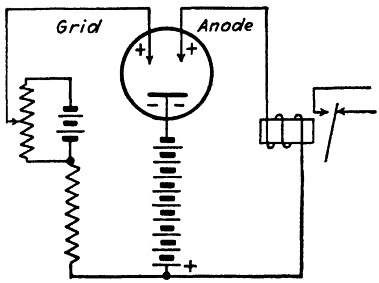


FIG. 154.—Principle of control with a negative grid bias.

Thereafter, however, the grid loses control and there is generally no proportionality between input and output. The only way to stop the discharge without resorting to the use of auxiliary circuits and devices designed for the purpose is to open the anode circuit or else to reduce the anode voltage below the extinguishing value. When, however, the anode current is either alternating or pulsating, the current strength falls periodically to zero and the discharge then is stopped. Whether or not it is to be started again on the following half-cycle is determined by the action of the grid.

In the testing of coin-collector relays, for example, a voltage increase of 0.2 per cent will stop the test and it cannot be started again until the voltage is corrected.

Because there always are two opposite currents, a current of electrons and a current of positive ions flowing in opposite directions, a grid in a gaseous discharge cannot stop the anode current once it has been started, as can a grid in a vacuum tube where only electrons (theoretically, at least) have to be dealt with. If the grid is positive there is an excess of attracted electrons near it due to the repulsion of the positive ions, while if it is negative, the electrons are repelled and an excess of positive ions is attracted near the grid, except at the critical grid potential which causes electrons and positive ions to arrive at the grid at equal time rates.

In connection with alternating currents, however, a number of useful actions may be obtained.

103. Some Types of Tubes.—It is obvious that there are at least two ways of controlling the gaseous discharge by a third

electrode or grid, one being to place it near the cathode to keep the gas ionized in that region, as is done in gaseous-discharge lamps, and the other is to place it near the anode, as has just

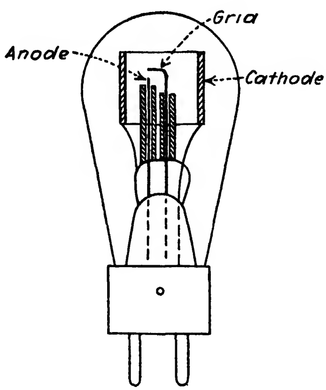


FIG. 155.—One form of supersensitive cold-cathode grid-glow tube or relay for low-power control circuits.

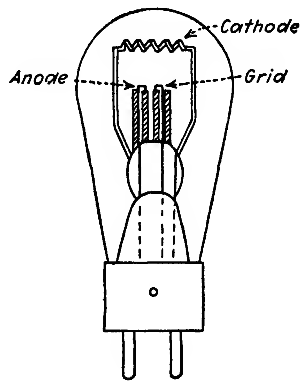


FIG. 156.—A form of hot-cathode grid-glow tube or grid-controlled rectifier capable of handling considerable power.

been discussed. It also may be placed in intermediate positions and more than one grid may be used (Art. 94).

The supersensitive cold-cathode grid-glow tube or relay for low-power control circuits shown in Fig. 155 has a large cathode surface and a relatively small anode with the grid close to the anode.

The hot-cathode tube in Fig. 156 is a modification of that in Fig. 155 and is capable of handling much more power.

Figure 157 shows one form of hot-cathode tube of a different construction, wherein the grid surrounds the cathode, which latter is heated by a resistor tapped at its middle. This type commonly is called a thyratron (Greek, meaning "a door").

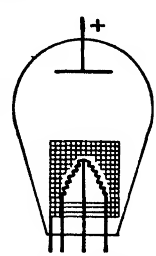


FIG. 157.—Principle of the thyratron.

All hot-cathode tubes are rectifiers, permitting current to flow in only one direction in the associated circuits with a given impressed voltage. Three-electrode tubes also may be used as inverters for changing direct current into alternating current at a frequency equal to that of the grid current and voltage derived from a small electric generator or a magneto of some kind.

104. Cathode-spot Tubes.—In this type of tube (Fig. 158) an arc constantly is maintained between the mercury pool and the "keep-alive" electrode, thus forming a source of electrons far beyond that which may be obtained with an oxide-coated filament and which will withstand large instantaneous current demands. The ignition voltage varies with the intervals between operations due to changes in the mercury-vapor pressure. The total voltage drop in the tube is only about 10 v.

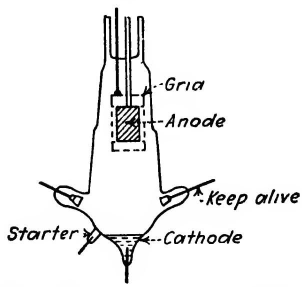


FIG. 158.—A mercury cathode-spot tube.

105. Operating Conditions.—Power gaseous-discharge tubes generally are operated at relatively high temperatures, due to the heat developed in both the tube and its filament or arc-heater, and it is important that they be not chilled too suddenly by contacts with cool objects or liquids. While this temperature has very little effect on neon tubes whose voltage drops are about 30 v, it does affect the ignition potentials of mercury-vapor tubes with voltage drops of about 15 v, and while the neon tube is ready for operation as soon as its filament is hot, the mercury tube does not reach a state of equilibrium until after the lapse of considerable time. Backfire, discussed in Art. 107, is apt to occur in small tubes as well as in the large power rectifiers.

106. Large Mercury-arc Rectifiers.—In large mercury-arc rectifiers used in electric traction, electrochemical processes and radio, graphite (or iron) anodes are brought out of the electrically welded steel tanks through vacuum-tight seals of high mechanical and dielectric strengths. Such large rectifiers have many auxiliaries, consisting of vacuum pump, transformer, circuit breaker, lightning arresters, filter equipment, switchboard and ignition-excitation set.

The mercury-vapor pressure and the temperature vary together, the best operating temperature being the practicable maximum. Vapor pressure doubles for each 10-deg (F) increase in temperature. Pressures of 5 ten-thousandths of a millimeter of mercury or less are common in rectifier operation. Pressures greater than 0.005 or 0.01 mm result in unstable or unsatisfactory operation.

All power rectifiers are water-cooled. Temperature regulation of the rectifier is effected by thermostatically operated water-valve and thermal relays, the rectifier being removed from service in case of prohibitive temperature and returned thereto as soon as normal conditions prevail.

The difference of potential or voltage drop from cathode to anode may vary from 20 to 40 v. When this voltage is low, the vapor pressure is high. If this voltage is high, the load is excessive and the vapor pressure must be increased or the load reduced.

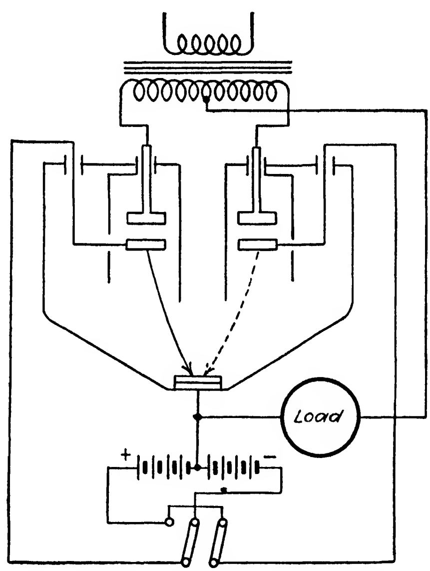


FIG. 159.—Scheme of large steel-tank mercury-arc rectifier. The battery and reversing switch merely indicate how the polarity of the grids or screens may be reversed.

The circular tank, crowned with its multiplicity (6, 12, 18, or 24) of anodes, reminds one of an internal-combustion engine as the anodes "fire" in the proper sequence.

Figure 159 shows such a (simple) mercury-arc rectifier with externally connected grids which block or release the discharge in the usual manner.

107. Backfire.—This term, as well as the term "arc-back" and "flash-back," is applied to short-circuits of the transformer secondary between the anode electrodes, when one is positive and the other negative (see Fig. 160), through the breakdown of the space charge, thus making the rectifier act as a two-way con-

ductor, short-circuiting the alternating-current supply line as well as the direct-current line or network which it feeds and causing interruption of service. Backfires are most apt to occur just as an anode ceases to be positive. While the cause of the phenomenon is not thoroughly understood, it is known that abnormally high vapor pressure, accompanied by a high current strength and a low difference of potential from positive anode to cathode, is a controlling cause and that it also usually occurs when this difference of potential exceeds 50 v. Impurities at the surface of the anode and condensed (liquid) mercury thereon also are known to cause backfire. The former emit electrons when incandescent and the latter at relatively low temperatures. A "silent backfire" occurs when the troublesome particle is vaporized during a half-cycle and without the tripping of the circuit breakers.

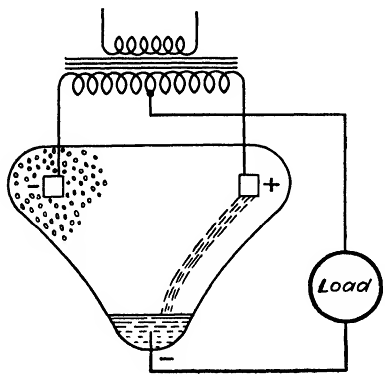


FIG. 160.—Illustrating positive ions about the negative anode electrode.

Grids were introduced near the anodes in the arc paths of power mercury-arc rectifiers to help prevent backfires. The function of the grid is to attract the positive ions and maintain the space charge at the instant when the anode ceases to be positive. These may be connected directly to the anode shields or left free (insulated). The grid takes its potential from the arc, thus being at a lower potential than its anode. For a short time after the arc stops flowing to the anode, the grid retains its potential, being negative with respect to the anode. Grids also are connected to outside sources of potential.

All remedies applied to reduce the occurrence of backfires in large power mercury-arc rectifiers, such as cooling the rectifier and keeping the vapor pressure low, moving the anodes away from the cathodes, placing them in shields, and placing grids in these shields so as to be interposed in the path of the discharge or arc, increased the voltage drop, the size, and the cost, but reduced the efficiency.

But the problem now appears to be solved. This best may be described by quoting an editorial in *Electrical World*, January 28, 1933, entitled "Rectifier Prospects Are Written Up by Pencil."

Discovery of a new arc principle bids fair not only to raise havoc with preconceived notions of rectifier dimensions but also to set new standards punctilious in performance. Joseph Slepian and L. R. Ludwig told at the A.I.E.E. convention of a simple but superlative control adjunct of the mercury rectifier which lends to the multiphase arc all the regularity and precision of mechanically timed automotive ignition. Grids are supplanted by it and down go anode-to-cathode distances and arc-space volume until the rectifier may at an early date fulfill the prediction that it would some day be only a fraction as big as the transformer which serves it. Along with this comes the certainty of ignition every cycle at any desired point on the voltage wave; also the phase segregation it entails precludes the spurious behavior of a negative anode of another phase.

None of these prospects was essayed in the paper which followed the conventional presentation of the academician who provides the technical tool and lets others worry or gloat over the consequences. The moderate voltage gradient maintained over the surface of a pencil or cylinder of high-resistance material projecting into the mercury bath is all that is necessary to attain continuous and absolute ignition of the arc at the interface between pencil and mercury.

The control comprises a high-resistance carborundum rod dipping into the mercury pool, thus dispensing with the grid, a sudden application of 250 v starting the arc in less than five microseconds.

108. Insulating Metals with Ions.—In high-voltage rectifiers there may be as great a difference of potential as 26 kv between two cold iron electrodes (graphite electrodes also commonly are used), but only a 25-v fall of potential or voltage drop in the discharge through the mercury vapor between one of them and the cathode, although the distance between the iron electrodes may be no greater than between either one of them and the cathode (Fig. 160).

In the first place, the breakdown voltage between the two iron electrodes is partly due to the fact that electrons are not readily emitted from cold metals, but the principal reason is that the negative iron electrode is insulated by the enormous numbers of positive mercury ions, constituting a positive space charge, which it attracts to it, these tending to neutralize the negative potential of that electrode. The electrons, on the other hand, are repelled away from the negative iron electrode and toward the positive electrode (then the active anode). Between this positive space charge and the positive electrode the electrons and positive ions

move about as though there were no difference of potential between the two iron electrodes.

This positive space charge also insulates other metals, making it possible to use steel envelopes or enclosures instead of glass. Owing to the vast numbers of free electrons flying about in the mercury vapor, all insulated metal parts receive a negative charge and thus have attracted to them a protective or insulating layer of positive mercury ions. Thus the interiors of steel tanks or cylinders, as well as all other insulated metals within them, are as well insulated from the rectifying mercury-vapor discharge or arc as though they were made of insulating material.

109. Not All Gaseous Discharges Possess Negative Resistance.—It has been found that the resistance of the gaseous discharge is negative in open arcs and for small currents at low pressures, that is, the fall of potential across a gaseous discharge decreases as the current strength increases. With moderate current strengths and low pressures a change in the current strength in mercury vapor has no effect on the voltage, whereas in low-pressure discharges, where all of the gas is ionized, the resistance is positive as in ordinary metal conductors, the voltage varying with the current strength. The only reason for a negative resistance is that the greater the current strength becomes the more gas is ionized. When all of the gas is ionized, however, the resistance becomes positive.

CHAPTER XIV

THE ELECTRONIC AGE

While the greatest present applications of the electronic tube are in communication, both by wire and by radio, it is finding ever increasing applications in industry, as will be evident from the present chapter as well as from those which follow. The application of the electronic tube to industry is destined to bring about even greater changes than did the application of mechanical power, which makes it difficult for us to realize that up to within about a century ago the great majority of men and women in the world were slaves or serfs and the world's motive power largely was muscular contraction, which would be about 3.6 million horsepower for the United States, instead of the billion horsepower now installed for all purposes, including lighting, if man depended upon his muscles instead of his machines.

110. The Progress of Technology.—Water power became sufficiently developed to compete with slave labor in some instances during the latter days of the Roman Empire, but it was not developed very much during the Middle Ages. At the end of the seventeenth century, as many as 500 horses were employed at one mine in England for pumping water. Then came the steam pumping engines of Savery and Newcomen.

The latter part of the eighteenth century witnessed the great inventions in spinning and weaving with machinery operated by mechanical power, while during the nineteenth century were developed machines with greater than human skill and almost human intelligence.

Up to about 1890, although electric street cars were in operation to some extent and electric lighting provided the principal generator loads, industrial plants still were mechanized throughout except for electric lighting. Line shafting was driven directly by reciprocating engines through the media of heavy belts, cables, and ropes, and factories literally were filled overhead with belts, shafting, and cumbersome pulleys and hangers, being multiplied wherever speed changes were required.

Then came the application of the electric motor to industry with the consequent elimination of the belt and cable drives from engines to line shafting, being supplanted by electric cables running to motors driving groups of machines. But each industrial plant had its own generator, belt-connected to the engine. Later on, the individual drive came into being, and the overhead shafting, hangers, pulleys, and belting, with all their expensive waste of energy, maintenance and delays, vanished in many cases. Even the engines disappeared to a great extent as electric power service was extended from the generating stations of electric public utilities to industrial plants.

The electrification of the industries, railways, elevators, and the usual equipment found in offices and the home, brought forth electromagnetic devices that converted electrical power into mechanical power for moving the auxiliary mechanisms which started, accelerated, retarded, stopped, and reversed, in their proper time relations, the motors, and other electromagnetic mechanisms controlled by either manual, semi-automatic or fully automatic means, as well as for their regulation and protection, and for the protection and sectionalization of power and lighting systems. These chiefly embody switches, relays, contactors, circuit breakers and lightning arresters, most of which are operated or controlled by electromagnets except in certain cases where small motors are employed for the purpose.

Such controlling, regulating, and protecting of electromagnetic apparatus have been developed to a point where it is thoroughly reliable, and enormous numbers of such devices are now in use. But "The old order changeth."

We now are entering a new stage of electrical development which eventually is destined to make obsolete vast quantities of the cumbersome, noisy and expensive electromagnetic apparatus and replace them with electronic tubes, and their associated circuits and nonmoving devices, which not only close and open all forms of electric circuits as swiftly as the lightning's flash and as silently as the passage of time, but regulate the voltages of generators and of lines; control frequency; rectify and invert currents; control power factor, and control industrial processes, as well as remote devices.

All of the highly developed electromagnetic switching, controlling, regulating, and protective devices have contacts that burn; pivots, bearings, slip rings, brushes, and other surfaces, that wear

and must be replaced; mechanical adjustments which must be made and which will work or wear loose, thus necessitating their being maintained and overhauled by skilled men.

When the electromagnetic devices are replaced by combinations of vacuum and gaseous-discharge tubes, effective and reliable service is obtained. There is no wear, noise, burning of contacts, or adjustments of any kind to be made, and they may be replaced in a jiffy at any time without interrupting the service, thus eliminating the cost of skilled labor.

Just as the cumbersome and expensive shafting and belting practically disappeared with the advent of the individual electric drive, so also will practically disappear the marvelous electromagnetic devices for the above-mentioned purposes, which are too expensive to be used anymore now that the electronic age has arrived. But electromagnetic devices will be increasingly developed and used wherever they will supplant more complex mechanisms in the construction of machines.

At the beginning of the present century one man could produce, for example, 1,000 letterheads per hour. To-day, one man can produce 20 times that number per hour, that is, he can do the work required by 20 men in 1901 on this particular job. All these results were brought about through technology—the application of science to the arts. And as technology constantly advances with new scientific discoveries, men are replaced by machines.

Just how our social order will emerge now concerns everyone, for technology will, no doubt, eventually free the human race from dull drudgery.

111. Electronic servants are silent and swift, almost instantly bearing messages to even the remote places of the earth; transferring people in ease, comfort and safety from place to place; automatically supplying light when needed; producing the health-giving vitamins in food; lightening the duties of the housewife, and so forth, almost without end. Great and small manufacturers constantly produce new labor-saving and comfort-giving devices and always are on the alert for new applications.

Electronic servants hear, see, smell, taste, and feel. One hears a command over a telephone and turns a large valve on or off. Another sees a fire and extinguishes it. Still another smells fumes and either sounds an alarm or sets a blower going to remove them. A fourth tastes fruit or a liquid and indicates its acidity.

Others have the sense of touch so highly developed that they can feel the presence of other bodies some distance away. All of these electronic senses are applied to industry.

The microphone is the electronic ear; the photoelectric cell is the electronic eye; acids and fumes change the electrical conductivity between electrodes or establish differences of potential between them, thus simulating the senses of smell and taste, while direct or distant "contacts," as through changes in resistance, self-inductance, or capacitance, simulate the sense of feeling.

The list of applications of electronic devices is long and varied. The absolutely automatic control of steam or electric trains from the safety standpoint is a good example. Others appear in the following chapters. We shall now return to some of the means whereby various forms of control are accomplished.

112. Phase Control.—Just one application of this principle is the control of light intensity in vast auditoriums, as for dimming the lights in theaters.

In principle, the circuit voltage is impressed upon the grid of a vacuum tube, the current flowing from cathode to anode when the phase relation of the voltage to that of the current is proper to permit it. Hence the power output may be controlled by changing the power factor, either by changing the value of resistance or capacitance in series with a condenser in the control circuit, or by other means. When the power factor is zero, no power will flow, but when it is maximum the maximum power will be obtained. In this manner any portion of the total available power may be passed by timing the voltage wave with respect to the current wave. All intermediate values of power are between these two extremes. Two vacuum tubes sometimes are employed which, in turn, control the grids of gaseous-discharge tubes in the output circuit.

The simple phase-control circuit in Fig. 161 employs a single gaseous-discharge tube. The portion of the half-wave on which the discharge through the load occurs is determined by the time required to charge the condenser through resistor *r* and thus bring the grid potential to the necessary value. When this resistance is large, the half-cycle is nearly completed before the discharge starts only to be immediately extinguished with the result that very little power is applied to the load. When the resistance is relatively small the discharge may start near the

beginning of a half-cycle and, once started, the discharge continues until the half-cycle is nearly completed when it is extinguished and restarted near the beginning of the next half-cycle.

The resistance *r* may be very great. A photoelectric cell may replace resistance *r*, when the resistance of the photoelectric cell may be varied merely by varying the intensity of the light falling upon its cathode. Photoelectric cells are discussed in the following chapters.

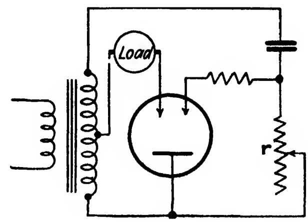


FIG. 161.—A simple phase-control circuit.

113. Inversion.—By the use of a circuit similar to that in Fig. 162, employing resistance coupling instead of transformer coupling between the small generator *G* and the grids, direct current may be converted into alternating current at the frequency of the small generator *G*.

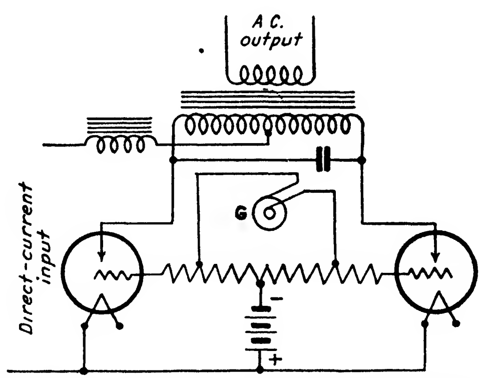


FIG. 162.—Changing direct current into alternating current at the frequency of the small generator *G*.

The grids are given a negative bias by the common battery shown. As the generator voltage swings to and fro, the grids alternately and periodically operate to permit direct current to flow through the respective halves of the primary of the output transformer, thereby inducing alternating voltage in its secondary and to the line.

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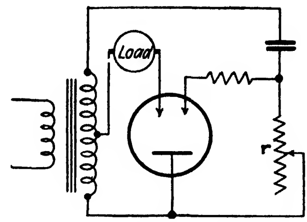

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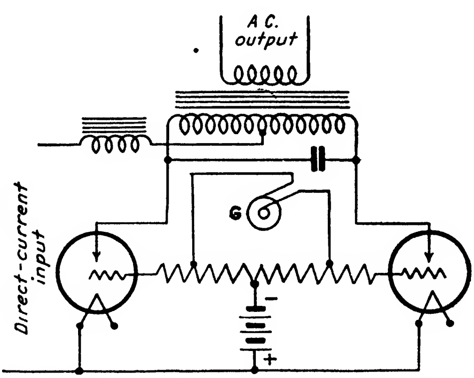

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circuits can be used to transmit 50 per cent more power. Since direct-current transmission would permit raising the voltage, fully three times more power can be transmitted thereby in the same system.

Other advantages are that generators could be designed for any frequency which would give the cheapest and most reliable operation; high-voltage oil circuit breakers would be replaced by gaseous-discharge tubes operating as both rectifiers and switches; short-circuit and synchronizing troubles would disappear; systems of different frequencies could be tied together; loads of various frequencies could be fed from a common supply, and all with greater safety and with complete control.

During 1932 there was installed in Boston a rectifier utilizing electron tubes taking alternating current from a 13.8-kv distribution system and supplying 250-v direct current to an Edison three-wire system.

Already the commutator on a motor has been replaced by electronic tubes.

115. Oscillator Control.—By means of an oscillator circuit somewhat similar to that in Fig. 134, wherein the capacitance is varied by the character of the material between its plates, the product may be measured and controlled in an entirely automatic manner as the material passes through; elevators are leveled by plates which change the capacitance and, therefore, the frequency of the circuit, and so forth There are a very large number of applications of this principle.

The principle is that when a circuit is tuned to resonance, the current strength is a maximum and any change in the capacitance will cause a reduction in the current strength. Thus delicate metal foil may be accurately gaged without touching it and, therefore, without distorting or otherwise injuring it.

In the October, 1931, number of *Electronics*, Olken stated that such a device easily measures to 1 ten-thousandth of an inch the thickness of a rubber sheet whose entire thickness is 0.0013 in. An ultramicrometer, capable of measuring to a millionth of an inch, also is illustrated and described.

These ultramicrometers are in use in pulp mills throughout North America, where they control the percentage of moisture in paper.

In all such processes wherein this device is used a slight change in thickness of rubber, for example, entails a loss. All such

variations not only are automatically corrected but also recorded in many instances.

The indicating instruments are calibrated in terms of thickness according to current strength.

116. Grid-Glow Micrometer.—This device, developed by Carson, will indicate displacements of one hundred-thousandth inch. The circuit is shown in Fig. 163. Pressure that would distort the specimen to be calipered is avoided through the sensitiveness of the contact to the grid, no pressure being required

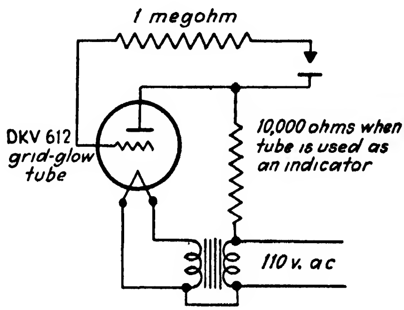


FIG. 163.—Circuit used by Carson for measuring displacements of the order of one hundred-thousandths inch.

by this method. Obviously, there are many applications in industry where this device may be usefully employed, as for measuring the diameter of very fine wire, the thickness of foil or of other ductile or plastic materials such as rubber or ceramic products that might be deformed by an ordinary micrometer. Already bottle caps are inspected by a grid-glow contact process, faulty caps being thrown aside as the bottles pass.

117. Other Uses of Gaseous-discharge Tubes.—There are many other uses of electronic tubes in industry, this chapter really being an introduction to what follows, and new applications constantly are being announced.

CHAPTER XV

LIGHT AND COLOR

When an electron combines with a positive ion, as in a gaseous-discharge tube or lamp, the electron oscillates rather violently before settling into its normal orbit, thus also affecting the entire atom which then radiates electromagnetic waves of such lengths (and frequencies) as to produce both visible and invisible light. Neutral atoms also emit light when heated.

Each of the 93 kinds of atoms is a complex broadcasting station which sends out its message, not at a single wave length as in the case of a radio broadcasting station, but at a great many simultaneously-transmitted wave lengths, that is, they appear to be simultaneously transmitted. Every atom is more or less in tune with every other atom of its particular kind, so when light energy is broadcast or radiated from atoms, all atoms in tune with any of the broadcasting atoms will respond and, therefore, absorb light energy, much as a radio receiver in tune with a broadcasting station absorbs some of the energy broadcast from it—otherwise there would be no radio reception.

It should be constantly recalled, however, that when we are dealing with single atoms and electrons, we do not obtain the same results as when we deal with the average electron or the average atom. Thus, while we know what a body consisting of a very large number of atoms will do under certain circumstances, and while we can calculate what a given current strength should be, we can only calculate by the laws of chance what a single electron or atom will do.

Furthermore, light energy or other electromagnetic energy, as in radio, does not travel like the waves of the sea, but in corpuscles of energy, called photons, with which, however, are associated mathematical quantities usually described as wave lengths.

118. Bodies and Light.—Luminous bodies emit light; transparent bodies transmit light; translucent bodies transmit light,

but objects cannot be seen through them; and opaque bodies do not transmit light. A ray of light is the direction of the line in which the light is propagated, and a beam of light is a collection of rays from the same source. The intensity or energy component of illumination on a given surface due to a point source of light varies inversely as the square of the distance from the source to the surface.

When light is transmitted through a transparent material, some of the energy is absorbed so that the emergent light does not have as much energy as the incident or entering light, and some of the wave lengths of the incident light are missing from the emergent light due to absorption. By using didymium goggles, the glass blower has the yellow glare of sodium gas completely cut off, but can see clearly the objects around him, by light of all the other wave lengths.

Bodies also reflect light, but the intensity of reflected light always is less than that of the incident light, due to absorption. The intensity of light from the sun is 600,000 times that of the light from the moon, the latter being reflected light. The angle of reflection of light is numerically equal to the angle of incidence. For example, if light strikes a reflecting surface at an angle of 30 deg it will be reflected at an angle of 30 deg from said surface, the angle between the incident and reflected beams, in this particular case, being 120 deg.

119. Color.—When all of the various wave lengths of all of the 93 kinds of atoms are broadcast simultaneously, as from the sun, the color of the light is said to be white, since the color produced without appreciable absorption by the irregular reflection (as from a rough surface) of a sunbeam produces the *sensation* of what we conceive as "white" in consciousness, but which is not an individual color but a mixture of all colors. On the other hand, when all of the incident light is absorbed, we have the concept of "black" in consciousness, but black is a complete absence of all color.

120. Refraction.—While the speed or velocity of light and all other electromagnetic waves, as heat and radio waves, in free space generally is given as 30 billion centimeters per second, it is less in all transparent solids and liquids than in air because they are more dense, being only about three-quarters as great in water as in air. The ratio of the speed of light in air to its speed in any other medium is termed the refractive index, or

index of refraction, of a body, being $4/3$ or 1.33 for water, but changing somewhat with temperature and wave length.

Refraction is the bending, deflecting, or changing of direction of an electromagnetic ray, as of light, heat, and radio waves, in its *oblique* passage from one medium to another of different density, or in traversing a medium whose density is not uniform. This may be observed in a small aquarium when light strikes it obliquely (Fig. 164). When light traverses such a plate (as

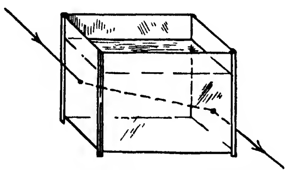


Fig. 164.—Light passing through an aquarium.

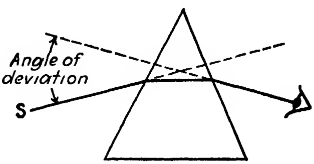


Fig. 165.—The bending of light by a prism.

any transparent medium bounded by two parallel plane surfaces is termed) of any uniform substance the emergent rays are parallel to the incident rays.

When light strikes a glass prism, as in Fig. 165, it is bent or refracted twice in the same direction so that objects seen through a prism appear deflected toward its top, the angle of deviation increasing with the refractive index of the material.

Every light ray has different color, and a beam of light consists of myriads of rays. The color of any object (as it appears to the eye) due to either reflected or transmitted sunlight, is the composite color due to the mixed rays that are not absorbed by a reflecting body or that "get through" a transparent medium.

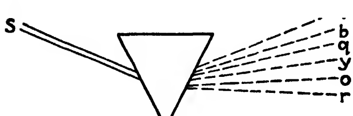


Fig. 166.—Dispersion. The sunlight from the small hole at *S* is dispersed into the colors violet, blue, green, yellow, orange, and red.

Due to refraction, when white light passes from one medium to another, as when sunlight passes through a small hole, as at *s* in Fig. 166, into a darkened room and onto a prism, it is decomposed into "all the colors of the rainbow," the phenomenon being termed *dispersion*. The rainbow is a continuous *spectrum* in the form of a band of light displaying the primary colors violet, blue, green, yellow, orange, and red, due partly to the refraction and partly to the reflection of light in drops of water falling through the air, resulting in the dispersion or separation of the

sunlight into its component wave lengths, thus giving an apparently continuous spectrum throughout the visible range from violet to red, the latter having the lower wave frequency and violet the highest. Thus the wave length of a violet ray is much less than that of a red ray.

121. Wave Length and Color.—Optics is that branch of physics which deals with the properties of light, so-called because light produces the sensation of vision, but, since light is emitted from the atoms themselves, it is but natural that it should have heating and chemical properties which are taken advantage

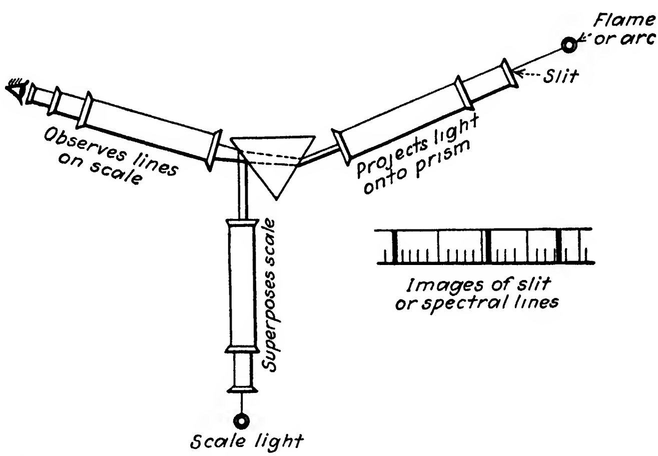


FIG. 167.—One form of spectroscope. The images of the slit on the scale are due entirely to gases.

of in measuring wave lengths in the individual portions of the spectrum. Thus delicate thermoelectric units are employed in the measurement of very long wave lengths, while the photographic plate is affected by light having wave lengths longer than the visible red light and shorter than visible violet, as well as by the light of the visible spectrum. These invisible rays are the infra-red and the ultra-violet light, respectively.

A definite color is nothing but a concept in consciousness due to electromagnetic waves of a definite frequency and intensity, or a mixture of frequencies and intensities. If we had a light receiver by means of which we could tune in on each wave length or wave frequency we simply would be tuning in on color. But this would require a receiver with an enormous number of possible settings "Station RED" would have very little

meaning unless the exact hue and intensity were specified, because we would find an enormous number of wave lengths in the "reddish" portion of the spectrum. But we have a means at our disposal whereby we can recognize each atom broadcasting, even though a number of different kinds of atoms may be chemically combined and simultaneously broadcasting as one station. This means is the spectroscope.

By the use of a prism and three telescopes (Fig. 167), for example, we can place a material in a flame or arc, pass a spark to or from it, or through it, if a gas; let the light emitted from it pass through a narrow slit and through a telescope to the prism, and thence to the observer's telescope. The third telescope with its source of light may be employed to superpose a scale on the colored images of the slit observed on the prism, so that the wave lengths corresponding to them may be measured.

Incandescent solids and liquids give continuous spectra, like the rainbow. Bodies at a red heat give only a long-wave spectrum, extending at most to the orange, but as the temperature gradually is increased, yellow, green, blue, and violet successively appear, while the intensity of the colors increases. When any substance boils, that is, changes to a vapor or a gas, the continuity of the varicolored spectrum disappears and "spectral" images of the slit appear here and there on the scale in various colors and, consequently, of various wave lengths. These are the "line" spectra of gases. In the visible spectrum of hydrogen, for example, there are bright lines in the red, green, and blue portions of the spectrum, as well as many others both visible and invisible. According to the laws that have been discovered, it would appear that it is theoretically possible for hydrogen, at least, to have an infinite number of wave lengths.

By means of certain characteristic lines in the spectrum of each element the presence of any elementary substance, even in the most minute quantity, may be detected in a mixture or chemical compound by examining its emitted light with the spectroscope. Caesium, rubidium, helium, and a number of other elements were discovered through spectrum analysis.

122. Diffraction.—A deviation of light rays from a straight course, as when passing near the edges of an opening or when partially cut off by an obstacle, is called diffraction; it is generally accompanied by prismatic colors due to interference. Diffraction spectra are produced by passing light through a series of

fine wires parallel to each other, or by careful ruling on a piece of smoked glass, or by photographic reduction from a carefully ruled drawing. The prismatic colors may be seen by partly closing the eyes and letting sunlight fall upon the eyelashes. Gratings also are constructed for reflection by ruling lines on plates of metal, as nickel.

123. Wave Lengths and Frequencies of Light.—The wave lengths of the various spectral lines have been carefully measured for the various kinds of atoms. Only a portion of these, however, are required to identify any kind of atom in a spectrum.

Units of light wave length are the millimicron ($m\mu$) and the Ångström unit (Å) (Art. 3, Table I). The visible spectrum extends over the wave length range from about 400 to 700 $m\mu$, or about 4,000 to 7,000 Å, the longer wave lengths being at the red end of the spectrum and the shorter wave lengths at the violet end. The corresponding wave frequencies are found by dividing the velocity of light by the wave lengths. Thus the wave frequency corresponding to a wave length of 700 $m\mu$ is 428.6 trillion, while that corresponding to 400 $m\mu$ is 750 trillion, waves or cycles per second. All visible wave lengths and wave frequencies fall between these values. As above stated, wave lengths also can be measured beyond the range of the visible spectrum and many such values herein mentioned are obtained either by sensitive electrothermal devices or by photography.

When sunlight is analyzed by the spectroscope it is found that there are numerous dark lines (absence of colored lines) in the solar spectrum. These are due to the absorption of some of the rays from the inner regions by atoms in the outer regions of the sun. The flame spectrum of sodium contains no red, orange, green, blue, or violet. It is marked by a very brilliant ray in exactly the same position of a notable dark line in the solar spectrum—Fraunhofer's dark line *D*. The arc and spark spectra of sodium, however, exhibit about 60 lines of varying intensities. In this connection, neutral atoms yield class I spectra; singly ionized atoms yield class II spectra; doubly ionized atoms yield class III spectra, and so on.

The wave lengths of the central portions of each colored region are about as follows: Red, 680 $m\mu$; orange, 640 $m\mu$; yellow, 580 $m\mu$; green, 520 $m\mu$; blue, 460 $m\mu$; and violet, 420 $m\mu$.

124. Apparent Colors of Bodies.—Bodies have no color of their own, the color changing with the nature of the incident light.

A body appears red in daylight, either when light is transmitted through it or is reflected from it, because it absorbs all other rays more than it does the red rays. Likewise, a body appears to be colored yellow, green or blue when these colors are absorbed less than all others.

When monochromatic (single-color) light falls upon a white body in a darkened room the color of the body becomes the same as the color of the light because it reflects all colors. If a body absorbs all colors but green, for example, then it will appear brighter in green light than in any other monochromatic light, because the green light is reflected or transmitted, depending upon whether the body is opaque or transparent. In this manner light may be filtered. Thus a green filter may be employed to permit only green light to filter through, or a combination may be used. A filter is a form of wave trap. The same holds for red, yellow, blue, and all other colors and hues.

If a body absorbs green light and reflects or transmits red light, then it will appear red in red light and black in green light. Reflection from an opaque body involves some penetration of the rays. Thus if a mixture of red and green rays strike an opaque body which absorbs green rays, only the red rays will be reflected and its color will be red under this light.

In all cases, the color of a body results from the mixture of the colors of the rays which have not been absorbed.

Compound or mixed colors which have the same appearance to the eye as pure spectral colors, but entirely different compositions, are obtained by the well-known method of mixing. Thus if one half of a disk is red and the other half is green, the color of the disk, when it is rotated (as in Newton's experiments), will appear very similar to the yellow (between red and green) of the spectrum. Thus green and violet yields blue, and so on.

125. Complementary colors are those which, when added together, will yield white. Thus, if the yellow and green rays of sunlight are deflected or obstructed so that only the red, orange, blue, and violet remain, when the latter rays are combined they form a brilliant purple. Hence when a brilliant purple and a mixture of yellow and green rays are combined, they yield white. Red and bluish green, orange and greenish blue, violet and greenish yellow, and green and crimson rays, are complementary colors which yield white when united, that is, they are complementary-colored *lights*—not as dyes, inks, or pigments.

To one with good eyes, the complement of any color may be found by the principle of "retinal fatigue," by gazing steadily for half a minute at some bright color a block away, and then shifting the gaze to a dot on a white sheet of paper. If the color "stared at" is red, the complementary color "seen" on the white paper will be bluish green.

Because dyes, inks, and pigments in general, absorb and reflect light, each one subtracts certain colors from white light and the color of the reflected mixture of rays is the complement of the color of the mixture of rays absorbed. Thus while the addition of yellow light to the proper shade of blue produces white light, when a yellow pigment is added to a blue one, the resulting pigment (not light) color is green because the yellow pigment removes the blue and violet rays by absorption, and the blue pigment removes the red and yellow rays, so that only green rays are reflected.

In three-color printing, the three primary colors are red, green, and blue-violet. The three so-called primary pigments are the complements of the three primary colors and are peacock blue, crimson, and light yellow. When the three primary colors are mixed, they yield white. When the three primary pigments are mixed they yield black. It is found that all colors can be produced by suitably mixing with the color disk the three spectral colors red, green and blue-violet. Hence the three primary pigments can be so combined as to reflect all colors in the desired manner.

126. The Normal Eye and Color.—The eye consists of the combination of an optical system and a photoelectric structure comprising a light-sensitive substance connected by a nerve system with the interpretive center of the brain. When light falls upon the eye, its spectral energy sets up an electrical response that is transferred to consciousness as color. The optical system of the eye (Fig. 168) is essentially a camera in which the cornea, aqueous humor, and the crystalline lens act as one single lens which forms an inverted image on the retina, an expansion of the optic nerve covering the inside of the back of the eyeball.

Color consists of two components: hue or tint, and intensity or brightness. A color of the spectrum is said to be a saturated color. The greater the admixture of white light with a spectral color the less is the saturation of the color. Color is a sensation and the eye is its sole judge, but the sensitivity of the human

eye to different colors varies with the individual. To some persons, pink and yellow, or blue and green, may appear the same. Such persons are mildly color-blind and cannot discriminate between slight differences in color. Others are afflicted with more severe forms of color blindness.

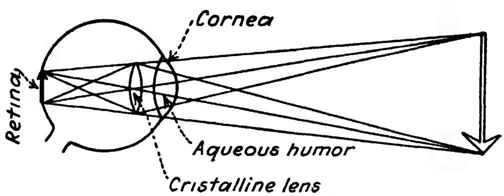


FIG. 168.—The human eye as a camera.

Thus while two persons may observe the same light source whose relative proportions of energy emitted at mixed wave lengths are constant, the relative response of the photoelectric structure of the eye to said frequency and energy may be different for each person.

The standard, then, is the color sensitivity of the average or "normal" eye, which has been measured by a number of investi-

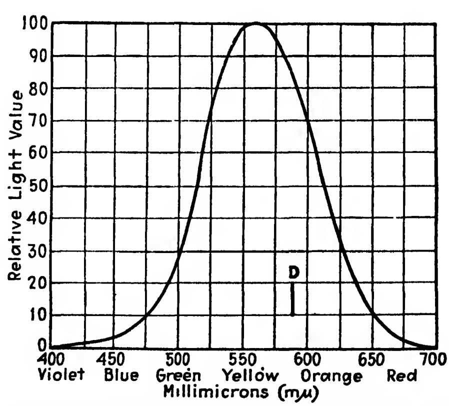


FIG. 169.—Normal visibility curve. The sodium line *D* also is shown

gators. The graph obtained by plotting the relative lighting value of the radiated energy against the various light wave lengths is known as the "visibility curve." This is shown in Fig. 169, wherein the colors of the spectrum and the sodium (*D*) line also are indicated.

The normal eye can distinguish about 180 hues or tints in the visible spectrum and about 33 variations in brightness or intensity of each hue, or more than 5,000 colors altogether.

127. Luminosity Charts.—Figures 170 to 175 are reproduced from those by Mailey in the article referred to in Art. 98. In

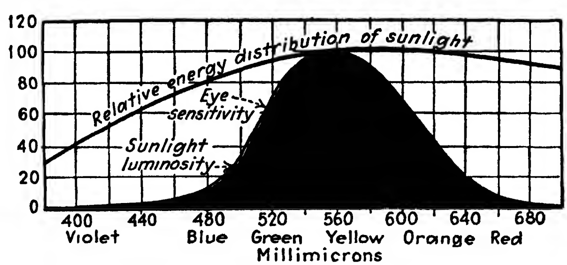


FIG. 170.—Sunlight luminosity curve.

Fig. 170 the relative energy distribution of sunlight is multiplied by the corresponding intensities on the visibility curve to give the luminosity curve or pattern of sunlight, whose area is a measure of intensity and whose detailed form is an indication of color quality, hue, or tint.

In the other charts the spectral lines are assigned arbitrary widths while their heights represent their relative intensities, the

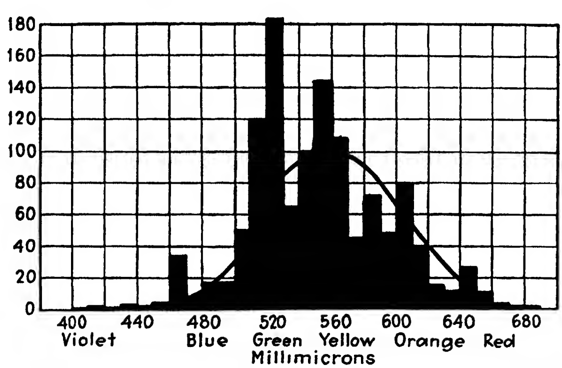


FIG. 171.—The light from carbon dioxide gas is a very close approximation of daylight of the blue quality of north skylight.

entire blackened area in each case being numerically equal to the area of the blackened sunlight luminosity curve in Fig. 170. Thus the luminosities represented by all of the curves in these charts or graphs are the same, and the variations in form from sunlight luminosity show color and whether or not it is produced

through the mixture of the complementary colors. The blacker a chart, the less gaps there are in the spectrum and the less is the "whiteness" dependent upon complementary colors.

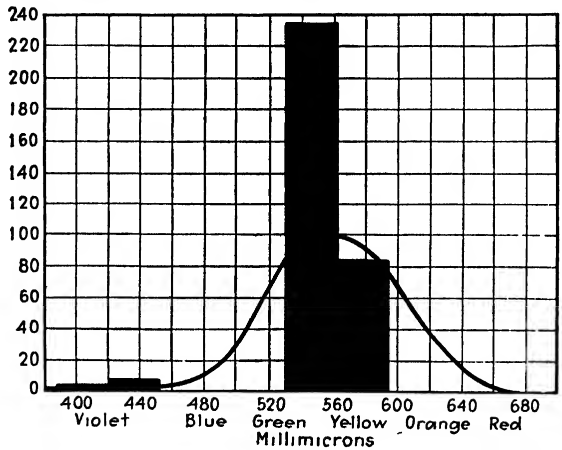


FIG. 172.—In the light from the mercury lamp there is a coincidence between the strongest lines and the eye sensitivity.

It will be observed that the light from carbon dioxide gas is a very close approximation to daylight of the blue quality of north skylight, used years ago in the Moore color-matching lamp. In the light from the mercury lamp there is a unique coincidence between the strongest lines and the eye sensitivity. The yellow-

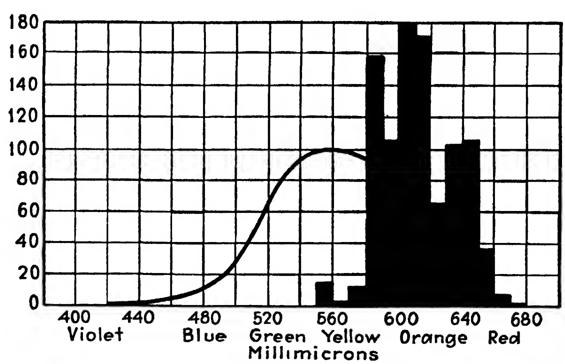


FIG. 173.—The uncomplemented orange-red light from a neon lamp.

green lines excite a white luminosity of pronounced blue quality, but when objects are seen by this light the absence of red and blue-green is evident.

The uncomplemented orange-red light from a neon lamp ordinarily is seen at so high an intensity that the luminosity lightens the hue to a yellow-orange, but at low intensities or

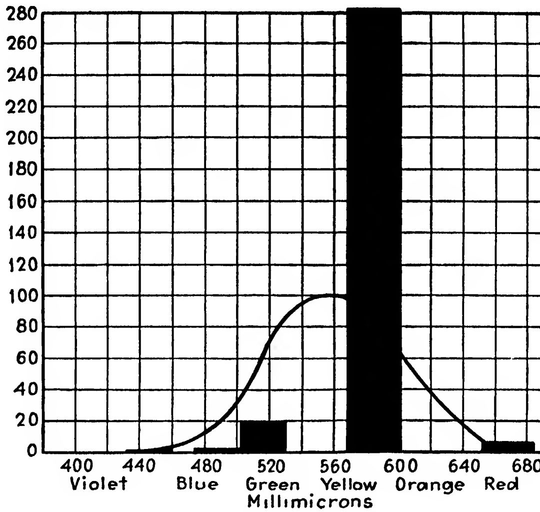


FIG. 174.—The light from a helium lamp owes its whiteness to a mixture of complementary colors.

through red filters this light may appear a fairly clear red. The light from a helium lamp is an outstanding case of apparent whiteness resulting from a mixture of complementary colors. There is in this light an excess of yellow and uncomplemented

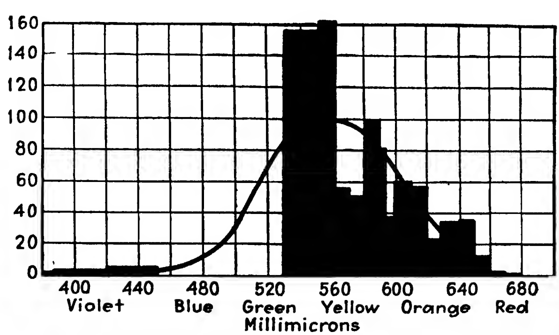


FIG. 175.—The light from a mixture of mercury and neon gas.

red which gives it its peculiar characteristic color of value for sign lighting. In Fig. 175 is shown the result of mixing mercury and neon gas in a commercial lamp for use with pan-

chromatic (all color) film. The red is well filled, and in practice the absence of blue is not found to be a serious matter.

The foregoing is abstracted from the article referred to above.

128. Color Definition.—For precision measurements of color (colorimetry) three methods are used: (*a*) the color is compared with mixtures of red, green and blue; (*b*) with a mixture of a color and white; or (*c*) the intensity is measured at various wave lengths.

In the October, 1930, number of *Electronics*, Ellsworth and McMichael have shown how difficult, if not impossible, it is to define color concepts in words alone; they also pointed out the inability to secure permanent reproducible color standards. Even if a set of color standards covering the range of the average eye sensitivity could be assembled, there would be no assurance that the different colors thereof would remain constant for any considerable period of time. Even such chemically stable substances as quartz are subject to slow change, while dyes or pigments used in printer's inks, for example, change considerably in even a relatively few hours when exposed to daylight, as shown in a set of curves from a test of covers of *Electronics* and *Donnelly's Red Book:* these curves show that the spectral distribution was greatly altered during the relatively short periods of exposure.

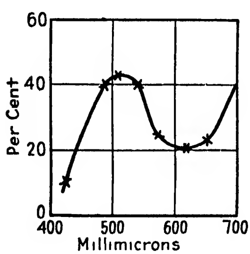


FIG. 176—Simple spectrophometric curve.

The data from a simple spectrophometric curve, as in Fig. 176 which is reproduced from the above article, accurately describe and define a color which can be recorded and reproduced at will. By taking the transmission or reflection factors at a few suitable wave lengths, so that the contour of its curve is approximately defined, it is possible to reproduce the curve from them. Their method, as described in detail in the above article, makes it possible to compute in terms of any theoretical or actual illuminating source, the spectral composition of the light transmitted to, or reflected from, a body. It points the way to a new definition of color values in terms of spectral energy distribution which would be definite, permanent and readily reproducible, as contrasted with present methods.

CHAPTER XVI

PHOTOELECTRIC CELLS

There appears to be a close connection between electrons and light. Thus oscillating electrons in atoms cause the emission of wave trains having exceedingly high frequencies and small wave lengths. When these wave trains strike matter they knock out electrons. This is the photoelectric effect. The peculiar nature of these wave trains is discussed first in order that the photoelectric effect may be understood better. Then follows a discussion of the various general types of photoelectric cells and their characteristics.

129. Action and Quanta.—*Action* is the product of energy and time. We are familiar with power, which we obtain by dividing energy by time; action, however, is not so familiar. Nevertheless, we meet with it in a number of ways. For example, the time rate at which electrical energy is converted into heat, as in a resistor when a constant current flows therein, is equal to the product of the square of the current strength and the resistance. Hence the electrical energy converted into heat in the resistor during any time interval whatever is equal to the continued product of the square of the current strength, the resistance, and the time of flow, or to the ratio of (*a*) the product of the square of the quantity of electricity that passes a given point in the resistor and the resistance to (*b*) the time interval.

It follows that the action—the product of the energy and the time interval—is equal to the product of the square of the quantity of electricity displaced past a given point and the resistance. Thus if, for example, 2 cmb are displaced past a given point in a resistor having a constant or average resistance of 10 ω, the action will *always* be 40 joule-seconds, or 400 million erg-seconds, regardless of the current strength. If the time interval is made smaller the expenditure of electrical energy will be greater, or if the time interval is increased the energy expenditure will be decreased, but the action will *always* be 400 million erg-seconds or 0.06103 trillion trillion trillion quanta, the *quantum*

being 6.544 billionths of a billionth of a billionth of an erg-second, and known as Planck's constant or quantum *h*. One joule-second is equal to 0.0015258 trillion trillion trillion quanta.

The quantum of action is one of the most fundamental quantities found in nature. It has been called "the atom of action," since it is the smallest amount of action, much as an electron is an "atom of electricity." Incidentally, the quantum of action has four dimensions, as has all action, and is a fundamental space-time quantity.

Nature broadcasts energy from the sodium atom at the frequency 509 trillion cycles per second, the period or time interval required for a single wave to pass a "fixed" point being 1.92 thousands of a trillionth of a second. This frequency produces the sensation yellow. It is the frequency of the sodium *D* line.

The broadcasting sodium atom, like all other atoms, stores up energy as it is heated or otherwise agitated and then suddenly emits it, similar to the manner in which a condenser-and-gaseous-discharge-lamp combination builds up a charge and then suddenly discharges it, the energy emitted by the sodium atom at each discharge always being 3.41 trillionths of an erg.

Since we know the values of the energy and the period, we multiply them and obtain exactly one quantum—the amount of action radiated from every kind of atom at each discharge. Other atoms discharge different amounts of energy at different frequencies, but the amount of *action* emitted or discharged and radiated into space at each discharge always is exactly one quantum in each case, whether the light is visible or invisible. This also holds for x-rays, gamma rays, and for other forms of radiation.

130. Electrical Charges Due to Light.—In 1887, Hertz discovered that violet and ultra-violet light tended to cause an electric spark to start more readily. He also discovered that ultra-violet light causes the discharge of negatively charged bodies, but not when in a magnetic field.

The *photoelectric effect* was discovered by Hallwachs in 1889. Crystals of fluorite not only became electrically charged by heat but also by exposure to sunlight or to the light from an electric arc, both of which are rich in ultra-violet light. Quartz becomes charged when exposed to sunlight, the edges of the prism being alternately negative and positive. An insulated metal plate becomes highly charged when exposed to sunlight. It has been

determined that every material is electrically sensitive to light, regardless of the state of that material. It may be an electric conductor, a resistor material, or a dielectric. All emit electrons when exposed to a *suitable* source of light.

Ultra-violet light, with an upper limit of wave length of about 300 mμ will cause solids, especially metals, to emit electrons, but the metals of the alkalis, lithium, sodium, potassium, rubidium, and caesium, given in the order of increasing atomic weights, are exceptions. They can be very sensitive in the visible spectrum and their upper limit of sensitivity sometimes reaches far into the infra-red. It is found that the more highly electropositive metals, such as sodium and potassium, give a greater emission of electrons under the action of light than do other metals under the same conditions, whereas for other metals, such as aluminum, magnesium, zinc, and so forth, electrons are ejected only by light of wave length smaller than 450 to 250 mμ, that is, by radiations in the ultra-violet. Liquids emit electrons when exposed to maximum wave lengths of about 180 mμ of ultra-violet light, while gases emit electrons when subjected to the much shorter x-rays. All such ejected electrons are termed "photoelectrons."

131. Light Quanta[1] and Photoelectrons.—When light falls upon metallic films of the alkaline metals, photoelectrons are ejected therefrom at high speed, and it is possible to measure their speed or energy experimentally, the speed depending upon the frequency of the light. Thus the blue light from the star Sirius will cause more powerful, though less numerous, electron ejections than full sunlight, because its frequency and energy are greater.

Einstein has shown that an ejected electron has a kinetic energy equal to the energy imparted by the light ray *less* the energy required to release the electron. This is the starting point of all photoelectric theory. Einstein derived his equation without knowledge of the manner in which the phenomenon took place, but when the experiment was made, it was found that Einstein was exactly correct.

The distance which the light quanta travel through space has nothing whatever to do with their effects when they strike and eject photoelectrons in photoelectric cells. Thus the light quanta which traveled at the speed of 186,000 mi. per sec. for 40 years before striking the cathode of a photoelectric cell, thus opening Chicago's 1933 Century of Progress Exposition, were just

[1] Now called photons.

as "strong" when they approached the telescope as when they left the star Arcturus 40 years before at the time of Chicago's 1893 Columbian Exposition. Owing to the distance of Arcturus, however, only a very small proportion of the light quanta radiated from that star at any instant 40 years earlier, ever reached the earth.

Apparently there is a very close connection between a light quantum or photon and an electron. While light appears to impinge upon matter as photons, it also appears to travel in wave form through space; whereas electrons (and also protons) seem to behave as waves when they strike matter but to travel as particles through space. According to Einstein, mass is radiated as energy. Thus, when 4 hydrogen atoms, each of the atomic weight or mass 1.0077, combine to form 1 helium nucleus of atomic weight or mass 4, the $0.0077 \times 4 = 0.0308$ part of mass is radiated away as energy. Russel recently stated that 4.2 million tons of heat are radiated from the sun every second as the mass left over from the element-forming process in the sun.

132. Kinds of Photoelectric Effects.—There are two general kinds of photoelectric effects, namely, the internal and the external. In the internal photoelectric effect, electrons are driven from the atoms of the structure of a conductor or semiconductor when exposed to light, thereby increasing the number of free electrons contained within the conductor and, therefore, causing a decrease in its resistance (see Art. 14). In the external photoelectric effect, electrons are driven from the surface of an electrode, thus causing a decrease in the resistance between that and another electrode.

133. General Types of Photoelectric Cells.—All of these cells respond to wave lengths in the visible spectrum, largely because the cathodes are not individual metals requiring ultra-violet light for their operation, except as noted above, and because they mostly depend upon matter in different forms.

A photoelectric cell may be regarded as a device with a cathode and an anode, between which the resistance decreases, or a difference of potential occurs, when the cell is exposed to light.

The fact that the resistance of selenium decreases when light falls upon it has been known since 1851 and it has been used in the production of light-sensitive elements, mostly for scientific purposes, since 1873. The photoelectric effect of selenium is of the internal kind. Cells employing selenium are called selenium

cells. They belong to the change-of-resistance or photoconductive class.

Photovoltaic cells, or light batteries, are of the wet or liquid type. They produce their own voltage so that an electric current flows in the circuit in which they are connected when light falls upon them.

The photoelectric tube, or phototube, consists of an alkaline cathode and a simple anode enclosed within a vacuum-tight glass bulb, although a quartz window is used for ultra-violet light since it is not transmitted through ordinary glass. By means of an external source of voltage, as a "B" battery, these electrons are driven from cathode to anode to form an electric (photoelectric) current, much as electrons emitted from a hot cathode are driven from cathode to anode in a thermionic vacuum tube to form a thermionic current. These cells are made in both the vacuum and gaseous types.

Semi-conducting, barrier-layer, or attenuating-layer cells of the cuprous-oxide-copper type, of the general order of the dry rectifier used in radio receivers, are like dry batteries in that they produce relatively large, low-voltage currents when illuminated.

Still another photoelectric cell consists of a flat, dry plate of metal with a suitably sensitized face, which merely requires a set of fingers making contact with the face and back to become a generator of electricity when exposed to light. This is called a "photronic cell."

The two latter types of cell are generators in that they convert luminous energy directly into electrical energy—a feat that has been accomplished by various methods for many years.

A cell with a grid inserted between the potassium cathode and the anode enables the modulation of the electron stream by an applied alternating current, thus simplifying the amplification or transmission of the resultant current; this, however, is a special cell not further considered herein.

Ordinary radio tubes make good photoelectric cells, and glow tubes also may be used for the purpose. Undoubtedly other devices will be found to make good photoelectric cells because the photoelectric effect is so universal.

Three million tiny photoelectric cells, so small that they can be seen only under a microscope—10,000 to the square centimeter—substitute for the millions of rods and cones behind the human retina in Zworykin's iconoscope, which promises to make tele-

vision practical. The cells are within a cathode-ray tube. Each cell has a tiny condenser associated with it, which is charged in proportion to the intensity of light falling successively on each cell. When the electron beam of the cathode-ray tube sweeps over the cells to discharge the condensers, the point-by-point transmission occurs.

134. General Requirements of Photoelectric Cells.—The "electric eye" is a light-sensitive cell which responds to both visible and invisible light in such a manner that changes in the strength of the electric currents in it and its associated circuits and devices, caused by corresponding changes in light intensity, make it possible to make accurate measurements of various kinds and to control as large amounts of power as may be desired.

Due to the vast speed of the inertialess light and the quick response of the photoelectric cell to it, self-contained and other units are finding ever increasing large numbers of applications in a variety of fields, the simplest being the interruption of a beam of either visible or invisible light, wherein the associated relay controlling the circuit, or circuits, containing the operating electromagnetic devices may cause them to function, either when an object comes between the light source and the photoelectric cell, or when a light-obstructing object moves out of the path of the light beam, or when a light beam is flashed upon the cell.

Extremely sensitive electromagnetic relays have been developed for this and other purposes. These, in turn, control contactors or larger electromagnetic switches which actually control the large amounts of power used in some cases. In this respect the photoelectric cell is a light-operated relay. Grid-glow relays often are employed instead of the electromagnetic relays, and gaseous-discharge tubes are replacing the contactors and other electromagnetic switches, as referred to in Art. 110.

Wherever a light beam can be interrupted, modulated, or controlled by some operation which is to be regulated, detected, indicated, counted, recorded, reproduced, and so on, a light-sensitive cell of some kind can be employed.

The desired characteristics of photoelectric cells are sensitivity, speed or frequency of response, linearity of response (wherein the current strength varies directly with the light intensity), reproductability of cells, color sensitiveness, and constancy, to which may be added low impedance in some instances, and low noise level or nonmicrophonic properties in cases where sound is to be

recorded or reproduced The first two characteristics may be the only ones required in a great many applications where a relay is to be operated for the purpose of merely turning power on and off, while neither may be of great importance when measurements of a bright-light source, as daylight, are to be made with the aid of sensitive instruments, like reflecting galvanometers; the linearity of response, however, is most necessary.

In television, sound-picture reproduction, and picture transmission, for example, the sensitivity, speed of response, and the linearity of response are all of prime importance. While the accurate reproductability of cells is always desirable, it is at this stage of development very difficult to obtain another photoelectric tube having the same characteristics as one purchased at some previous date. It is particularly desirable in the measurement and comparison of colors wherein the color sensitiveness of the cell should be substantially constant, as in applications where it is necessary to purchase special filters for a piece of apparatus the operation of which is dependent on a definite color sensitiveness.

The spectro or color sensitivity of a photoelectric cell is its response to various wave lengths of light of equal energy in various parts of the spectrum. It may be expressed in terms of percentage of the maximum or peak response to monochromatic or single-color light of equal energy and various wave lengths.

Constancy is particularly important in all cases where a cell is used in making measurements, for if the cell "drifts," incorrect results will be obtained. The constancy of a cell is affected by its insulation and the charges upon its walls.

For maximum sensitivity, photoelectric cells should be provided with an optical system, that is, with suitable lenses.

While none of the types of photoelectric cells approaches the ideal requirements for specific use, all are extensively used.

CHAPTER XVII

SPECIFIC TYPES OF PHOTOELECTRIC CELLS

The list of photoelectric cells constantly is growing. The characteristics of some of the best-known types of cells and the methods of sensitizing some of them are discussed in this chapter. The modern photoelectric cell is an excellent example of a product of science and engineering. It has been said that the photoelectric cell really became useful only when the engineers became interested in it, but what science has done and is doing, not only in pioneering but also in perfecting it, also is very much in evidence.

135. Selenium or Photoconductive Cells.—The resistance of selenium changes when exposed to light. Selenium is the metal most commonly used in this change-of-resistance type of cell. It has long been experimented with and but recently developed by engineers. At present it is being used to perform such general functions as reproducing sound pictures in a large chain of theaters, detecting smoke in steamer holds, controlling the flow of oil in oil-burning furnaces, turning on and off street lights, and so forth; its frequency of response, however, is somewhat less than that of some other types. The selenium elements are enclosed in vacuum tubes.

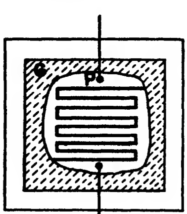


FIG. 177.—One form of selenium cell.

In one form of selenium cell (Fig. 177), a platinum deposit P on a glass plate G is divided into two dovetailing parts by a scratch upon which selenium is painted in such a manner as only to bridge the scratch. It is claimed that current-strength changes of 0.5 to about 25 ma. may be obtained with this type of cell in which the ratio of dark to light resistance may be 10 or more, this current strength being sufficient to operate a relay.

In the Thirring cell, an assembly of alternately interleaved sheets of copper foil and mica (Fig. 178) form a bridge, upon the side of which is placed a spot of selenium of about 2-mm diameter

and 0.05-mm thickness. It appears that the selenium extends between the leaves by capillary attraction, thus giving an extremely intimate contact. It is stated that with the maximum polarization of 30 v a sensitivity of 40 ma. per lumen is attained; however, the amperage is somewhat less for higher frequencies as used in practical sound motion picture reproduction.

The Burgess "radiovisor bridge" consists of a glass tube with a three-element prong base. The element is a flat glass plate, upon the front side of which two interlocking comblike gold electrodes are fused in place and covered by a thin layer of selenium-like enamel. The cell can be used to operate a relay direct, a special vacuum-contact relay having been developed for this and similar purposes. It is stated that the bridge is responsive to high frequencies or rates of change in light intensity as used in sound reproduction.

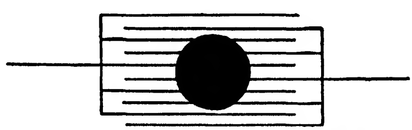


FIG. 178.—Principle of the Thirring cell.

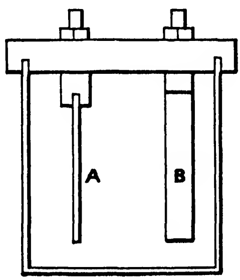
Merely placing selenium elements in vacuum tubes is not sufficient to make the cell thoroughly reliable, according to claim. The element of the G. E. FJ-31 selenium tube consists of a glass plate on which a layer of selenium is deposited between two electrodes. The selenium surface is formed entirely in vacuum by a method similar to that used in vaporizing metals in thin films on the bulbs of radio receiving tubes. A pure, dry gas is admitted during the annealing process, and it is allowed to remain in the tube. The maximum current strength at 125 v, either alternating or direct, is 0.5 ma. The ratio of dark to light (100 foot-candles) resistance is 8. The unit is mounted in a tube with a standard socket base.

It is claimed that the selenium bridge is so sensitive that a flashlight will cause it to operate its associated mechanism at a distance of 50 ft.

Thallofide cells containing an oxygen compound of thallium sulphide on a gold and quartz support are said to exhibit the greatest change in resistance when dealing with infra-red radiations. In both thallofide and selenium cells, inertia begins to become troublesome above voice frequencies.

The maximum color sensitivity of the selenium cell is at about 680 mμ, falling off to about 10 per cent at 600 and 900 mμ, respectively, but persisting at substantially this value to about 400 mμ, in one type. Hence, the maximum color sensitivity is in the red and infra-red, which makes it very sensitive in its response to light from an incandescent lamp. Its linearity of response is good, although the curve is not a straight line. The selenium cell is of the high impedance type.

136. Photovoltaic Cells or Light Batteries.—This type of cell depends upon chemical action for its operation, a difference of potential being produced upon its exposure to light; therefore, no



A. Cuprous oxide.
B. Lead.
FIG. 179.—Principle of the photovoltaic cell.

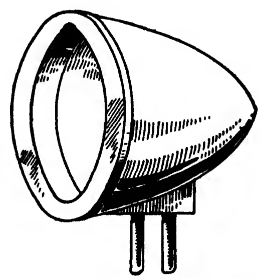


FIG. 180.—General appearance of one form of photovoltaic cell.

external battery is required to operate its associated relay. A cell having about 6 sq. in. of electrode surface will deliver about 25 ma. when exposed to indirect sunlight. Current strengths as great as 150 ma. may be obtained from such cells having sufficient electrode surface. The electrodes may be lead and cuprous oxide, with lead nitrate as the electrolyte. A section of the cell and the general outline of one form are shown in Figs. 179 and 180, respectively.

This type of cell also is called a "photolytic" cell. It has a low impedance of about 500 to 1,500 ω, depending upon the frequency. Its output is rather high but poorer than that of the caesium and potassium photoelectric tubes, and its response characteristic is good, being better than that of selenium. The fact that it requires no external voltage is an advantage in many cases. It has given satisfactory results in sound-on-film reproduction, as well as in many other applications.

137. Vacuum Photoelectric Tubes.—This type of photoelectric cell consists of a surface of one of the metals of the alkalies, with a metallic rod, ring, and so forth, spaced and insulated therefrom, enclosed in an evacuated glass bulb and connected in an electric circuit containing a source of polarizing voltage. The circuit also may contain a galvanometer, a microammeter, or a resistor suitable for impressing voltage upon the input side of a vacuum tube. The alkali metal is the cathode, and the other electrode is the anode.

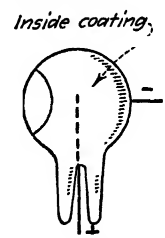


FIG. 181.—One form of photoelectric tube. The inside coating is the cathode and a vertical rod or wire is the anode.

When light strikes the alkaline cathode surface the photoelectrons move from cathode to anode in the manner already described. The caesium type is preferred for general purposes because it is the most sensitive to red light and, therefore, to the light from incandescent lamps. While the current strengths obtained with this type of cell are only a few microamperes, large voltage changes may be obtained across a resistor through the corresponding changes in the small current strength due to the high resistance of the resistor. Figure 181 shows one form of this type of photoelectric cell.

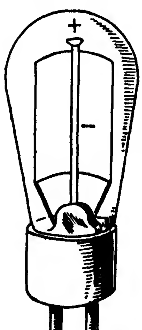


FIG. 182.—Photoelectric tube with a plate cathode.

There are two general methods of making these tubes. In the form shown in the above illustration, a portion of the inner surface of the glass (or, in some cases, quartz) bulb is coated with an alkaline metal to form the cathode; this may be done by electrolysis. Glass is not a solid, in the ordinary sense, but is a solid solution, as mentioned in Art. 64. Therefore, electric currents can be conducted through it by electrolysis. When the bulb is dipped into molten sodium and a current flows from the salt through the glass to an incandescent filament inside, sodium is deposited inside the bulb. When the salts of other alkali metals are placed inside the bulb and a current is passed through the glass to the sodium salt outside, the sodium inside the bulb is replaced by potassium, rubidium, or caesium, as the case may be, to a depth of about 0.002 mm. Films of these metals also may be obtained in this general manner.

The other general form of this type of cell has a plate for the cathode, as in Fig. 182, which is alkaline-coated and sensitized. Both forms are sensitized as described below.

The normal sensitivity of this type of cell generally is sufficient for making measurements when sensitive instruments are connected in circuit with it, or when connected with it through a vacuum-tube amplifier, but it may be made very much more sensitive by a sensitizing process.

Thin and invisible layers of caesium or potassium, one atom (monatomic) thick and thicker, are deposited on other metals to form the cathode. According to Schroeter, cells with a monatomic layer of caesium upon oxidized silver foil have their highest sensitivity near 700 mμ, and it is claimed that with the energy distribution of an ordinary tungsten-filament lamp (2,410 deg C) these caesium cells give almost as good results as gas-filled hydrogen-treated potassium cells, described below. Furthermore, by forming a monatomic caesium layer upon a surface of a salt or oxide obtained by distillation, caesium upon caesium oxide, 12 ma. per lumen could be obtained in a high vacuum cell, or one electron per 50 light quanta, as against 0.17 ma. in the ordinary cell.

The response to yellow and red may be enhanced by treating the cathode surface with sulphur vapor or oxygen, or both, and almost any spectral sensitivity distribution may thus be obtained.

Vacuum photoelectric tubes are very stable and suitable for many purposes. They are inherently high-impedance photoelectric cells, but their linearity and frequency of response are good.

138. Gas-filled Photoelectric Cells.—These are similar to the vacuum photoelectric cells and are more sensitive, generally having from five to ten times the current response of the former.

The sensitivity of a photoelectric tube is greatly increased by producing a spark discharge in such a cell filled with hydrogen or some inert gas under low pressure, some of the alkali metal, as potassium, being ionized by ionic bombardment. Investigations have shown that in order to increase the sensitivity of a potassium layer, the potassium vapor must be brought into contact with the gas which is present.

Suhrmann has shown that the cathode of a sensitive photoelectric tube consists of three layers: a conducting support, a film of a metal compound, and a film of pure metal. Selective

emission appears when a thin film of potassium is deposited on silver which has been slightly oxidized by passing a spark discharge through the cell, the sensitivity shifting toward longer wave lengths with an increased maximum emission. With a thicker potassium film the surface assumes a violet color, the sensitivity in the yellow decreases slightly, but the peak in the blue becomes still higher. When the potassium film becomes visible to the eye, however, the entire emission drops to low values. The relative sensitivities are shown in Fig. 183.

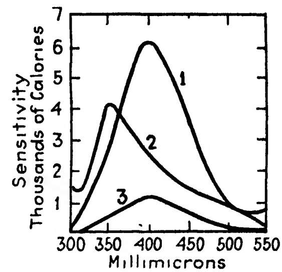


FIG. 183.—Effect upon sensitivity of varying the thickness of the film. 1. Invisible film of several layers of atoms. 2. Monatomic film—one layer of atoms. 3. Visible film.

By using various screens, the color sensitivity of different photoelectric tubes was investigated by Atkins, Poole, Young and Pierce. They found that red-sensitive cells consisting of a thin film of potassium on oxidized copper, became green-sensitive when hydrogen was introduced. They withstood 140,000 meter-candles at 120 v, equivalent to full daylight, giving 19 ma. Quartz-envelope cells containing a thin caesium oxide layer on a silver-plated copper sheet were found to have a maximum sensitivity at 700, a minimum at 500, a sharp maximum at 360, and a sharp minimum at 320 mμ. Other quartz-caesium gas-filled cells have been found to be sensitive in the ultra-violet region of the spectrum.

The above examples are selected to show that the color sensitiveness of photoelectric tubes may be varied by various forms of treatment. There is much literature on the subject. The tendency, however, is to make photoelectric tubes more sensitive to white light by enhancing the response in the red region.

The caesium type of photoelectric tube is the one most commonly used because of its greater sensitivity. Its ionizing potential usually is about 90 v. The potassium type has been successfully operated on voltages ranging from 150 to 275. One manufacturer has announced a series of photoelectric tubes of caesium and silver oxide highly sensitive in the red region of the spectrum. It is claimed that by a special treating process the sensitivity of these cells has been increased to a value in excess of 100 μa per lumen, uniformly high sensitivity having made it possible to supply these cells with a somewhat higher ionizing

voltage than previously. In all cases, it is well to obtain the operating characteristics of cells from the manufacturers, as the positive ion bombardment of the sensitive surface at higher potentials will eventually destroy the sensitivity of the cell and shorten its life, although the cell may not be injured by ionization or glow for short periods when a suitable resistance is included in the circuit.

Fourmarier found that the photoelectric current of potassium and caesium cells containing neon, argon, or helium, increased in two steps when exposed to a brightly illuminated slit within 10 microseconds, first along a rapid slope, and then more gradually. It has been suggested that the lag is due to the time required for ionization by positive ions or to the establishment of a space charge.

The high sensitivity of gas-filled photoelectric tubes is due to the production of vast quantities of ions which disappear less rapidly than they are formed, particularly if high voltages are employed for more sensitivity. The effect is more pronounced in some gases than in others. In order to obtain a comparison, Schroeder and Lubszynski filled a discharge tube containing two plane electrodes a few millimeters apart, with helium, argon, and a mixture of argon and hydrogen at low pressure. After passing a discharge through the gas and stopping it, the conductivity of the gas was measured with an applied potential of 30 v. While ions could be detected in neon and helium for four or five minutes after the discharge had been stopped, no trace of charged particles could be detected one second after the stopping of the discharge in a mixture of argon and a small percentage of hydrogen. Since it is known that no metastable (not entirely stable; condition in between stable and unstable) atoms can exist in argon when hydrogen is present, the very small lag of cells appears to be due to the formation of metastable atoms. Photoelectric tubes filled with pure hydrogen could be used in television experiments up to 70,000 changes per second, but the hydrogen pressure could not be kept constant with the construction used.

Small photoelectric currents may be measured easily by counting the number of discharge flashes in a neon tube.

139. Barrier-layer Photoelectric Cells.—The well-known cuprous-oxide rectifier used in radio receivers and the like has for its elements a disk of copper and a film of cuprous oxide thereon produced by heating the copper in a furnace and then quenching

it. An outer film of black (cupric) oxide also is produced, and this is removed by a brief dip in a solution of sodium cyanide. When an alternating potential is applied across the interface between the mother copper and the oxide film the conventional current flow from oxide to copper is about 1,000 times greater than in the opposite direction. This means, of course, that electrons flow more readily from copper to oxide.

In 1924, Grondahl and Geiger discovered that the cuprous-oxide rectifier disk acts as a photoelectric cell and constructed such cells with a contact made to the oxide by means of a flat spiral of copper wire pressed down by a glass plate. Light transmitted through the glass and between the turns of the copper spiral penetrated the oxide film and generated a potential difference at the interface between the oxide film and the mother copper, so that the latter became negative with respect to the former.

In 1930, Lange announced that with a cuprous-oxide cell having an area of 2 sq. cm he could produce 500 μa per lumen. He sputtered either an opaque grid or a transparent film or a combination of both on top of the oxide which had been formed on the mother copper in the usual manner. The effect of the light was localized on the back of the oxide, as described above. The Lange cell is known as the "reverse" or "rear-wall" type.

Shortly after Lange's announcement, Duhme and Schottky described another type of cell which yielded 5 ma. per lumen, the light being supplied by a gas-filled tungsten lamp. The Schottky cell consisted of a plate of pure crystallized cuprous oxide, entirely independent of, and unattached to, any unoxidized copper, one surface of which was etched and then sputtered with a translucent film of some metal such as gold or silver. This type of cell is called a "barrier-plane" or "obverse" type.

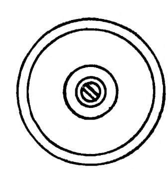


FIG. 184.—Appearance of laboratory mounting of cell.

Investigation seems to show that the effect of light is to eject electrons from the oxide into the adjacent electrode. If the two electrodes are connected by a zero-resistance conductor, all of the electrons will return therethrough, that is, an equal number of electrons will return.

Wilson has described how an obverse cell may be made from a standard rectifier disk, in the October, 1932, number of *Electronics*, from which the foregoing was abstracted and from which Figs. 184 and 185 are reproduced.

In the Lange cell, the vacuum of the photoelectric tube is replaced by a copper-oxide barrier-layer which separates the cathode (a film of copper so thin as to be transparent) from the anode which also may be of copper. This cell operates like the photolytic cell to the extent that no auxiliary voltage is necessary. The sensitivity, which extends over the whole visible spectrum with the maximum occurring near the infra-red, is about the same as that of the gas-filled alkali-metal tubes, or ten times that of a vacuum tube, and the cost of production is far less. The internal resistance is only several hundreds of ohms.

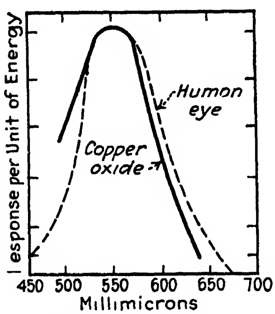


FIG. 185.—Color curve of copper-oxide cell compared with that of the human eye (normal visibility curve).

The sensitivity of the Siemens and Halske cuprous-oxide front-wall cell, which has an active surface of 3 sq. cm, is said to vary with the wave length in about the same way as that of the human eye, but the response in the blue varies from cell to cell by 30 to 60 per cent, and temperatures above 70 deg C injure the cell. Its temperature coefficient is about 1 per cent per deg C.

There are many other cells of this general type, of which the "photronic" cell is a form which has been very carefully developed and constructed. Figures 186 and 187, showing the characteristics of the "photronic" cell are reproduced from an article by A. H. Lamb in the April 16, 1932, number of *Electrical World*. Its general appearance is as represented in Fig. 188.

Hertz discovered that ultra-violet light causes the discharge of negatively charged bodies, but not when in a magnetic field, as mentioned in Art. 130. Rupp found that the photoelectric current obtained from cuprous-oxide rearwall cells decreases in a magnetic field with the square of the magnetic field strength, the decrease being smaller in liquid air than at room temperature but most pronounced when the sensitive surface is parallel to the direction of the magnetic field. Inertia effects also appear in commercial cells. Thus, with a magnetic field strength of 4,200 gausses (maxwells per sq. cm) the relative decrease in the current strength was 0.5 and the increase in resistance was 1.1. When the magnetic field strength was doubled, the decrease in the

current strength and the increase in the resistance were quadrupled, being 2 and 4.5, respectively.

140. Photoelectric and Thermionic Emission.—The filaments of thermionic tubes are coated with oxides to enhance the emission of electrons therefrom, so that the filaments may be operated at lower temperatures but with greater electron emissions. A very desirable filament for thermionic emission consists of a platinum alloy whose surface is coated with a mixture of barium

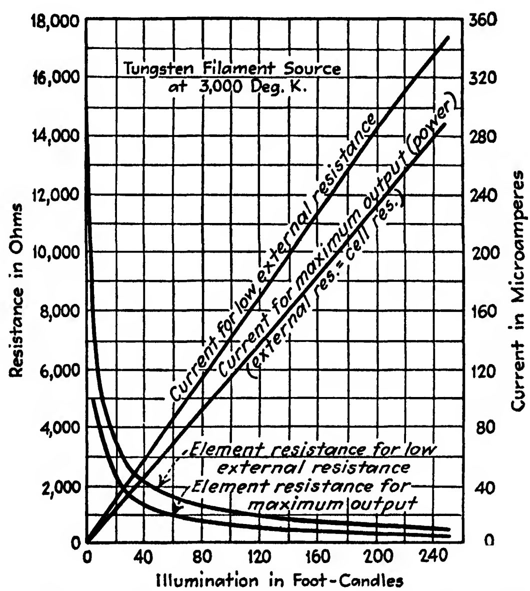


FIG. 186.—Characteristics of the photronic cell, showing that its voltage varies inversely with its resistance, thereby making the number of microamperes proportional to the number of foot-candles of illumination.

and strontium oxide, a very minute amount of barium, but enormously increasing the emission for a given temperature. Why the electron current obtained from a single layer of barium atoms on a platinum filament is so enormously greater than the current obtained from a filament of either substance alone has been one of the basic problems of the tube industry.

It appears that the metal used as a filament is not of prime importance in the production of an active coating and that positive ion bombardment and electrolysis are important factors in the production of an active surface.

Newbury, Lemery, and Ramadanoff examined the photoelectric effect from barium-oxide-coated filaments. At the maximum, the photoelectric current was thirty times smaller than the thermionic current.

In measuring the emission from thin films of caesium, Koller used a perforated disk to interrupt the light, so that the photo-

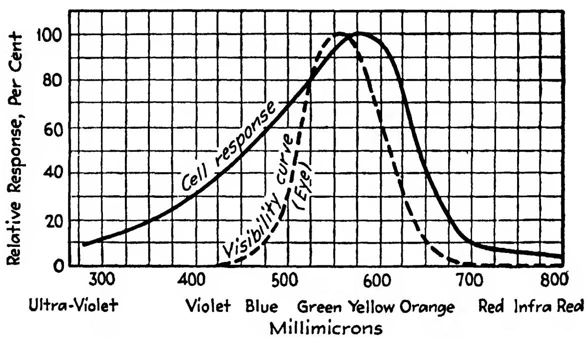


FIG. 187.—Color response of the photronic cell. Since the cell is more sensitive than the eye in the red and blue regions, the color response may be cut down with filters to approximate that of the eye.

electric current would be pulsating and transmitted through a resistance-capacity-coupled amplifier. Since the thermionic current is direct, it would not pass through. In this manner the two currents were separated.

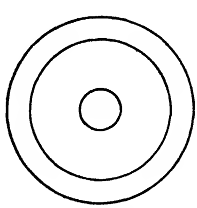


FIG. 188.—General appearance of photronic cell.

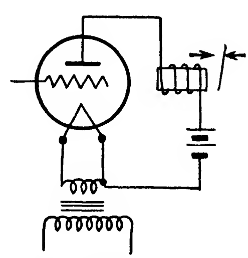


FIG. 189.—Circuit for using UX-245 tube as a photoelectric cell.

141. Radio-tube Cells.—In a number of tests reported by Koechel in 1932, it was found that ordinary black-plate radio vacuum tubes, as the UX-245, act as light-sensitive cells if the grids are left "floating," as when disconnected by cutting off the grid pin, and making sure that there is no base or socket leakage to cause electrons to leak from the grid. It is necessary

that the tube be clear on top so that light may have free entrance to the grid, tubes with mica top supports giving the best results. He found that the floating grid of any vacuum tube will assume a charge of about 1 v negative, which charge acts as a bias. Hence if the plate voltage is reduced, the plate-current strength will remain constant until the grid is illuminated from an outside source, the relation of plate-current strength to light intensity being very constant.

Apparently the light causes the grid to emit electrons more rapidly than it can accumulate them. The filament voltage must be low enough to minimize the effect of light from the filament, yet high enough to produce the required plate current. A plate voltage of 22 v or more should be used to operate a relay (Fig. 189), like a Western Electric type B-40 of 400 ω resistance operating on 1.5 ma., only 4 to 10 v being required when an indicator or meter is employed.

Initial tests on various tubes showed that the body-capacity effects were very pronounced, necessitating the shielding of the tube for light-response purposes. It would appear that the body-capacity effect could be employed advantageously in advertising and the like, after the general manner of that use of the grid-glow tube.

142. Effects of Large Photoelectric Surfaces.—The photoelectric tubes used in television are large because of the small amount of reflected light received by them from the scanning surface, three or more cells sometimes being required for the purpose.

Large cells are not inherently more sensitive. If the light is condensed by an optical system there is no advantage in using a larger cell. There are, however, advantages in using large cells in connection with daylight recorders without the use of an amplifier.

Fleischer has described a large photoelectric tube, constructed by silvering the inner walls of a well-evacuated Dewar flask and depositing caesium on this surface of 1,200 sq. cm. A metal screen placed midway between the walls acts as the anode. When placed in the sunshine coming through a closed window, it produced 250 μa without any appreciable potential, the current obtained without any applied potential being nearly 70 per cent of the saturation current obtained with about 2 v. The photo-

electrons produced a potential difference of 1.25 v between the anode and cathode placed 1.5 cm apart.

An advantage of long photoelectric cells is that the current strength may be increased without increasing the light intensity, merely by flooding more and more of the sensitive surface with light from a fixed source. A use of this principle is suggested in the following chapter.

CHAPTER XVIII

GENERAL METHODS OF USING PHOTOELECTRIC CELLS

Ever since man inhabited the earth, light and darkness have had pronounced effects upon him, his flocks, and his crops, sending him off to sleep when darkness came and filling the earth about him with fantastic goblins of his imagination. But with the return of the sun he went forth to his labor. Now man has learned how to make light and darkness control the actions of the robot machines of his own creation. The general methods of bringing this about, as herein described, obviously have many applications and variations. From these simple beginnings have been developed the systems of automatic control, regulation,

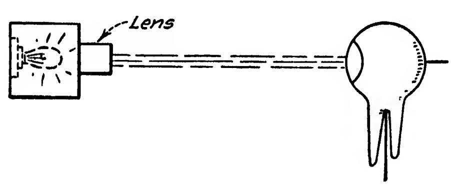


FIG. 190.—Incandescent lamp as a light source for the operation of a photoelectric cell.

testing, and so forth, that are destined to bring about vast changes in industry as well as in our social system. The block system of representing apparatus is employed to some extent in this chapter.

143. Simple Principles.—A simple method of employing a photoelectric cell is to place it where a beam of light from a suitable source, as an incandescent lamp, will fall upon it. The light from the source may be concentrated into a beam by means of an optical system consisting of one or more lenses, or a parabolic reflector in certain cases, to cause the light outside the container of the source to be transmitted as a beam to the photoelectric cell before which another optical system may or may not be placed, although one is required in such cases as sound-on-film reproduction and where the light is to be passed through slits.

The light beam may be transmitted directly to the photoelectric cell as shown in Fig. 190, wherein the light source is at a distance from the cell; it may travel to a reflector, whence it is reflected back to a photoelectric cell either near or separated from the light source (Fig. 191), or it may be transmitted through, or reflected from, a solid, liquid, or gas to be examined.

144. Interrupting the Light Beam.—While the light beam may be turned on only when a selected photoelectric cell is to be excited, as when a crane operator directs a light beam upon a cell on or near a soaking pit in a steel mill to cause its cover to be lifted by the associated mechanism, the light beam preferably is maintained at constant intensity from a lamp source operated at

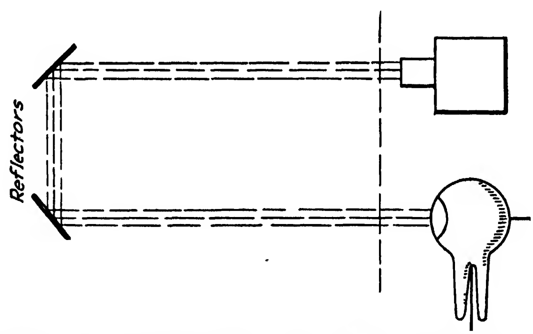


Fig. 191.—Method of placing the light source beside or near the photoelectric cell.

less than normal voltage so as to maintain the constancy and prolong the life of the lamp.

Changing the intensity or quality of the light falling upon a photoelectric tube is very similar to changing the grid potential of a vacuum tube, inasmuch as it causes corresponding changes in the cathode-to-anode current strength.

The light beam may be either wholly or partially interrupted, depending upon the function to be performed. This is best illustrated by examples.

Let a hole be drilled or a slot be cut through the scale of an indicating meter, as a galvanometer, microammeter, voltmeter, weighing scale, and so forth, as in Fig. 192, and also through the back of the instrument case wherever practicable, so that when the needle of the meter is exactly over the hole the light beam will be interrupted. A stop of some kind should be provided to prevent the needle from passing the hole in the scale.

It is obvious that when a predetermined *effect* is produced, as when the needle covers the hole and interrupts the light beam, the *cause* may be controlled in some manner through the action of the photoelectric cell on its associated apparatus.

The meter may indicate temperature, pressure, force or weight, power, current strength, voltage, distance, height or depth, and so forth, all of which may have a cause whose effect is indicated either electrically or in some other manner upon the indicating

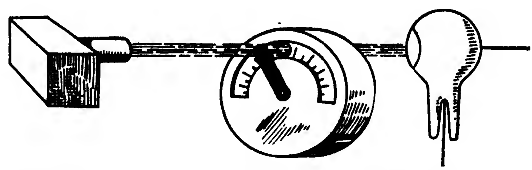


Fig. 192.—When the needle of the indicating instrument interrupts the light beam, the photoelectric cell ceases to function, thereby causing a relay to perform some function.

meter whose needle covers the hole in the scale when the limit of tolerance is attained.

This simple principle has an enormous number of applications, as in the automatic regulation and control of the various limiting conditions imposed, and also in the automatic testing of electrical and other equipment and materials wherever an indication is made by some kind of instrument, as to resistance, capacitance,

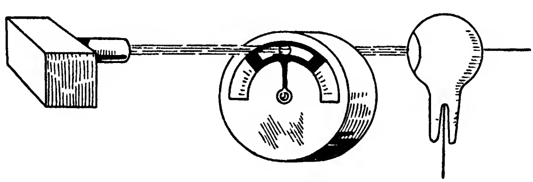


Fig. 193.—Method of interrupting the light beam through both maximum and minimum effects.

self-inductance, frequency, voltage, and any of the causes which produce limiting effects, as in automatic weighing and the like.

The control of the effects which cause the interruption of the light beam may be through maximum or minimum indications, or both, that is, by the use of either two holes or two light beams, or a special needle with a slot (Fig. 193) whereby a single or double light beam may be employed, or by other arrangements. Thus both maximum and minimum effects may control the

causes, as when a pump is automatically stopped when the pressure reaches a predetermined maximum and is started again when the pressure reaches a certain predetermined minimum value.

All of the various positions of the needle at various instants also may be recorded simultaneously, as by a graphic recorder, if desired.

145. Graduated Control.—In other cases, the intensity of the light from the source controls the action of the photoelectric cell

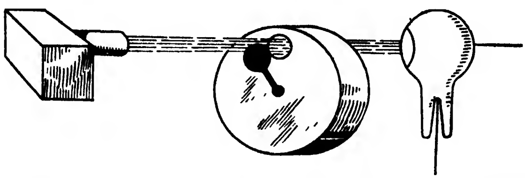


Fig. 194.—Eclipse method, operating on the principle of quantity of light. This merely illustrates that light gradually may be cut off from the cathode surface of the photoelectric cell. The principle is illustrated in Fig. 195.

on its associated apparatus, as in graphic daylight recording, sound-on-film reproduction, and television transmission. The transmission of light through smoke, gases, liquids, and solids, and its reflection from bodies to be detected, sorted, graded, and so on, also are of varying intensity.

In all such cases, graded control and regulation, as well as the simple on-and-off control, usually is accomplished through the use of either electromagnetic or gaseous-discharge relays con-

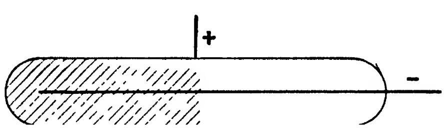


Fig. 195.—When substantially one-half of the cathode surface is in a shadow, the photoelectric current strength is reduced.

trolled by the photoelectric cell through amplifiers when required. It is possible to adjust these relays in such a way that different ones will operate on different current strengths, or at different voltages, proportional to the intensity or the quality of the light falling upon the photoelectric cell, thereby making it possible to grade objects reflecting light in different intensities into a number of classes according to shade.

An eclipse method is illustrated in Fig. 194 wherein the light intensity is constant but the quantity of illumination varies.

Such a method might be applied to a long photoelectric cell wherein the current strength would be increased or diminished, not by the intensity of illumination, but by the quantity of light upon its sensitive surface (Fig. 195). Thus, when one-half of this suggested photoelectric cell is in a shadow, as shown, substantially one-half of the total current strength will be obtained.

This general effect also may be obtained by means of a reflector mounted on some moving object, as the mirror of a reflecting galvanometer (Fig. 196). In this general manner a number of separate circuits successively may be energized as the light beam successively falls upon different photoelectric cells. This is illustrated in the block diagram in Fig. 197 wherein the blocks or squares represent the associated amplifiers, batteries, and other necessary apparatus, and wherein the graphical representation of photoelectric tubes is employed.

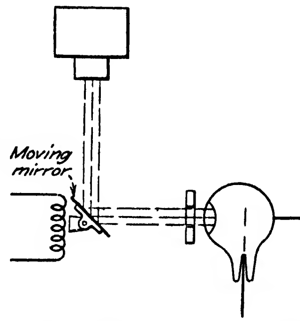


Fig. 196.—Control of the photoelectric current by means of a movable mirror, as on a mirror galvanometer. The device shown merely illustrates the general principle.

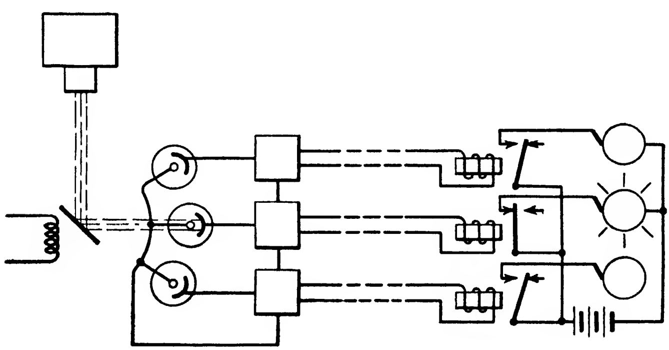


Fig. 197.—Controlling various circuits through a single light source and a controlled mirror. An incandescent lamp indicates the excited circuit in this instance.

146. Simple Photoelectric Circuits.—For the reasons stated in the preface, circuit constants are given only in special instances, but the required data may be obtained with equipment.

The simplest circuit is shown in Fig. 198, wherein a battery may or may not be required, depending upon the type of photoelectric cell employed.

Figure 199 is an extension of the same circuit, wherein amplification is obtained by means of a vacuum-tube amplifier, voltage changes across resistance R, due to changes in the strength of the photoelectric current, being impressed upon the grid of the vacuum tube in the usual manner.

FIG. 198.—Simple photoelectric circuit.

An amplifier circuit requiring only one "B" battery is shown in Fig. 200 wherein R is of the order of 10 megohms.

Figure 201 shows a simple Wheatstone bridge, commonly used in the measurement of resistance (Art. 85), wherein photoelectric tubes are substituted for the standard resistance and the resistance to be balanced with it. Since the photoelectric tube really is a variable resistor, it is obvious that the resistance of the two tubes will vary with the intensity and quality of the light falling upon them. This general scheme is employed in color matching.

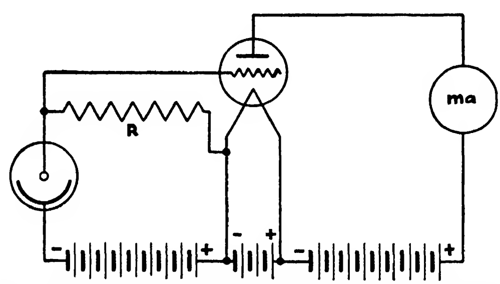


FIG. 199.—Simple amplifier for photoelectric currents.

The radio-tube photoelectric circuit is shown in Fig. 189, Art. 141.

For precision work, the vacuum-tube voltmeter circuit, of which there are many kinds, is employed as an amplifier. Figure 202 shows such a circuit as described by Tulauskas, wherein only the variation of the plate current is employed. This is said to be very accurate. The primary photoelectric circuit in Fig. 198 has been inserted in the present diagram, with a resistor replacing the galvanometer and used as a coupling; a relay may replace the indicating instrument in the output side if desired. The circuit constants shown are those given in the original diagram.

The circuits in Figs. 203 and 204 are those developed by the Burgess engineers for the operation of relays with the selenium bridge.

In Figs. 205 to 207 are shown three circuits used in sound-on-film reproduction, as described by Wyeth. The cathode heater connections are not shown. The captions explain the uses.

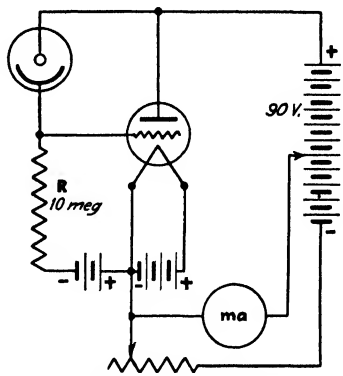


Fig. 200.—Amplifier circuit.

In this connection, photoelectric tubes cannot be used on extension cords of any appreciable length at any desired distance from the amplifier, because the inter-conductor capacitance constitutes an impedance in parallel with the photoelectric tube. By using shielded cable, however, to keep the inter-conductor capacitance as low as possible, the cable may be made many feet in length if desired, a cable 4 or 5 ft. long being suitable for most purposes. Such a cable is employed in a G. E. photoelectric unit.

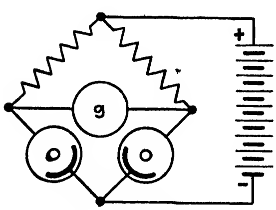


Fig. 201.—Wheatstone-bridge method of comparing light intensities and colors.

A G. E. circuit for turning lights on and off by means of a selenium cell and a thyratron is given in Fig. 208.

Another selenium-cell circuit is shown in Fig. 209.

147. Photoelectric Relays.—While the term "relay" generally is applied to those of the electromagnetic, vacuum, or gaseous-discharge types—of which there are many of each kind on the market, from extremely sensitive to very rugged forms, some of the electromagnetic relays being of the mercury type which open and close their contacts in vacuo—a photoelectric relay refers to a complete unit containing a photoelectric cell, an amplifier (if required), and a relay of some kind, whereby a change in the intensity, quantity, or quality of light at the light-input side causes some form of control to take place at the output side, although an additional wire is required to bring in the power with one of the output wires which acts as a power input wire.

There are a number of good photoelectric relays on the market. In a G-M photoelectric relay all wiring, including that of the light

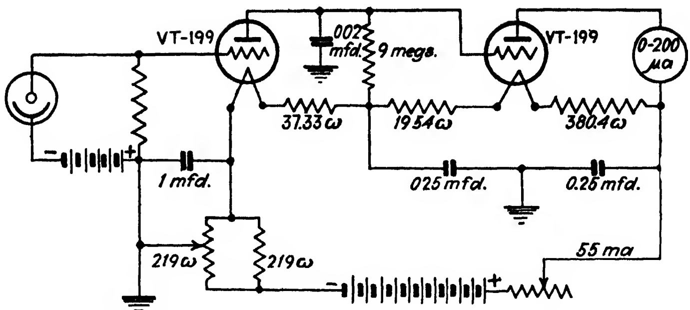


FIG. 202.—Vacuum-tube voltmeter circuit for amplifying photoelectric currents.

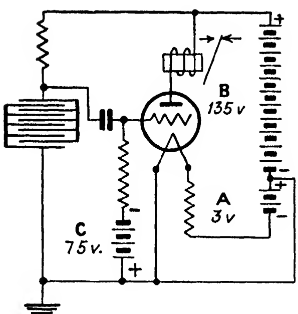


FIG. 203.

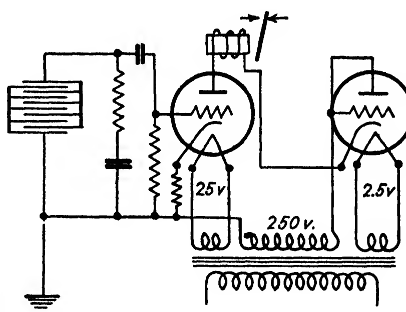


FIG. 204.

FIG. 203.—Impulse circuit for dry-battery operation with a vacuum tube and power relay. Vacuum-contact relays preferably are used.

FIG. 204.—Impulse circuit for alternating-current operation with bridge feeding heater-type tube actuating power relay.

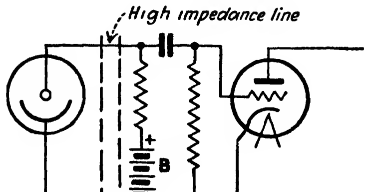


FIG. 205.—Circuit generally employed where the head amplifier is mounted adjacent to projector.

source, is connected at one point, the rays from the lamp being focused by a lens on a special mirror which occupies little space, and thence back to the photoelectric relay. The unit is said to be capable of operating at speeds as high as 600 light interruptions per minute.

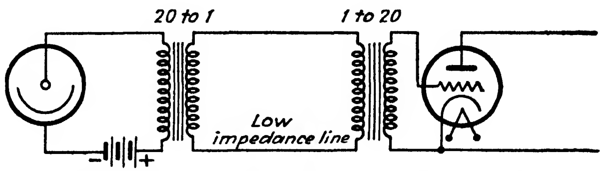


FIG. 206.—Circuit used for coupling high-impedance photoelectric cells to amplifiers remote from the projector.

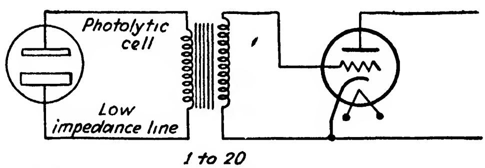


FIG. 207.—Coupling circuit used in connection with low-impedance photoelectric cells. Note that no battery is required when a photolytic cell is used.

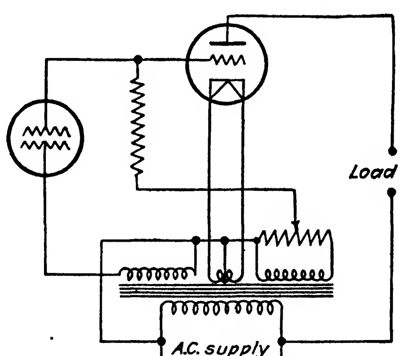


FIG. 208.—Selenium-thyratron system for illumination control.

The reflection principle also is employed in smoke recording and control.

Time-delay relays, of which there are both electromagnetic and vacuum types available, may or may not be included in photoelectric relays between the sensitive relay contacts and the contactor or gaseous-discharge control tube, to prevent too sudden operation, as in lighting control, for the response of the photo-

electric cell is very fast and it is undesirable to have lights, for example, switched on and off every few seconds as on a semi-cloudy day.

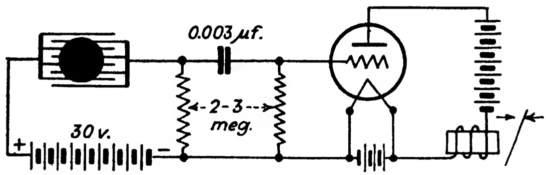


FIG. 209.—Resistance-coupled selenium-cell circuit.

As an example, one unit employing a standard 112-A tube and operating on 110-v, 60-c circuits, will operate at any reasonable distance that light can be transmitted. Either reflected or diffused light will operate the unit which is adjusted at the factory for operation requiring the light from a 10-w lamp placed 1 ft. away, without the use of a reflecting lens.

CHAPTER XIX

USES OF PHOTOELECTRIC CELLS

While photoelectric cells have long been used by scientists in connection with galvanometers in making physical measurements, their use was greatly extended after engineers made them more practicable through development and coupled them with amplifiers. The fundamental value of the photoelectric cell is that the photoelectric current strength varies with the intensity, quality, or quantity of the light falling upon it and its color selectivity. Hence the term "electric eye." It is the eye of the television transmitter and of the sound-on-film reproducer in talking motion pictures. Its color sensitivity makes it invaluable in grading articles according to color. Its response to light intensity enables it to sort and grade objects according to size and shape, as described below. The simplest and most general application, however, is its control of some kind of relay so that power may be turned on at one light intensity and turned off at a different light intensity. This feature is discussed first. The applications mentioned in this chapter show the general scope of the photoelectric cell and will suggest further applications.

148. Duties Performed by Photoelectric Cells.—The widest application of the photoelectric cell is in control, either by sudden "on-and-off" actions of a relay controlled by it; control in "steps" of light intensities or quantities; or by gradual variations in them. Thus in the control field alone the photoelectric cell has a tremendous number of practical applications.

In the field of safety, guarding and protection it also has an enormous number of practical uses. It also acts as a detector and gives alarms. In counting, sorting, grading, recording, inspecting, measuring, reproduction, and color matching, and even in music, its application constantly is being extended.

The human eye is a marvelous organ. The electric eye is an aid to the human eye, extending its usefulness and range, and it

can be made to see colors not seen by the human eye, thus enabling scientists to explore high- and low-frequency variations above and below those to which the human eye will respond. And the electric eye never sleeps—it does not even wink.

149. Examples of Photoelectric Control.—At the opening of Chicago's 1933 Century of Progress Exposition the lighting circuits were switched on by light from the star Arcturus which left it 40 years before, at the time of Chicago's Columbian Exposition of 1893.

The famous Elm Tree range light on Staten Island in New York Harbor automatically is switched on and off exactly when needed. It may be turned on half an hour earlier on a stormy day or very much earlier if a heavy thunder storm approaches, going off whenever there is sufficient light.

A photolytic cell, designed to admit light from almost any angle of approach, has been developed for mounting, as at the tops of rotary beacons at small airports, for controlling the flood and boundary lighting at the approach of an airplane, equipped with landing lights of approximately one million candle power. The cost of operation of such a system is very small and it eliminates operating the equipment for long periods when there is no aircraft in the vicinity.

Huge advertising signs automatically are turned on as daylight wanes, as on cloudy days or at dusk, thus dispensing with time switches and using the signs to the best advantage. Street and aviation obstruction lights are controlled similarly.

There is a tremendous opportunity for light control in schools, offices, stores, public buildings and homes. After a three months' test of a photoelectric light control in a schoolroom, it was found that artificial lighting was used about a third of the time, and that the average grades of the students in the test room were considerably higher than those in the other half of the same class in another room. As a double check, the two sections of the class were then switched, and again the new class in the test room showed marked improvement over those relegated to natural lighting and manual control.

On a year's test in a machine shop it was found that one-half of the electric-light bill was saved by photoelectric control. Janitors and others responsible for turning on and off lights often are elsewhere, or too busy, when needed. Furthermore, the human eye has other duties besides watching just one thing—

the intensity of daylight. But the electric eye will eternally watch on just one job, and it never forgets to act.

To avoid sudden changes in light intensity which would confuse the vision of the drivers on entering and leaving a vehicle tunnel in Paris, photoelectric cells are employed to control the light intensity inside the tunnel to correspond with the natural illumination outside. Thus on sunny days all the lights are on. On gray days, every other bulb is glowing, and on dark days or periods one light in four is used. At night every eighth lamp is turned on.

Indoor advertising signs operate at the approach of a visitor, thus functioning only when they will be observed. At a business show in New York, every time a visitor reached for a circular, an automatic typewriter wrote out a message.

Car headlights turn on roadside advertising signs and also cause garage doors to open. One country home, at least, is equipped with photoelectric cells concealed in stone walls about the place so that whenever a visitor's car comes up the driveway, a battery of 300-w flood lights are switched on and chimes are rung. In light-beam traffic control, when the driver approaches a main traffic artery and automatically interrupts a light beam, the signal is set to permit the cross-traffic to go ahead.

Self-opening doors in restaurants, to permit waitresses to pass with trays; in shops, warehouses, mines, and so forth, for hand trucks and the like, also are in use. In a self-opening door in an English restaurant a spring coil attached to the door draws back and opens it. The apparatus and labor involved cost less than $150 in England.

In the control of temperature by photoelectric cells, milliammeters or voltmeters are calibrated in terms of temperature. When the furnace is started, light shines through a hole in the meter and onto a cell, and the heating circuit is closed. When the higher limit of temperature is reached, however, the needle covers the hole and strikes a stop to prevent its passing, and the light beam is interrupted, thereby switching off the heating current. As soon as the hole is clear again, the heating current is turned on by the light beam. Mercury-switch relays are employed. The fundamental control element is a thermocouple between the oven-heating coils.

In direct photoelectric control methods, as in annealing and tempering furnaces where pyrometers formerly were used, the

visible radiated energy is a measure of the temperature. The photoelectric current is amplified, as by vacuum tubes, and indicated or recorded on a meter calibrated in terms of temperature. The same current may operate a grid-glow relay to control the supply of fuel to the furnace. The advantage of such a method over the pyrometer is that since no part of the apparatus is in the furnace it does not deteriorate due to the action of any products of the furnace. By using two grid-glow relays, it will control between limits, 1,000 deg C being the lowest limit. The electric eye simply looks at the furnace wall or some object in the furnace. Since the radiation from a hot body varies much faster than its temperature, this method of measurement is very sensitive. A suitable optical system is employed, as usually is the case with photoelectric cells.

In a voltage supervisor for maintaining constant voltage or current strength, a light beam is focused through the two holes in a meter and onto a photoelectric cell which operates an alarm or performs other functions when the voltage varies.

Limit switches are employed to measure, or to limit, length of travel of various objects, such as parts of machines. Such objects either move shutters at the limit of travel to cut off the light beam directly or to move a "flag" into, or out of, the light beam.

In a sheet mill, where the sheets are too thin to operate mechanical switches, the sheets intercept the light beam which can be turned out, or the photoelectric circuit switched open, when manual adjustments have to be made. In a steel mill, bars leaving the rolls at a maximum speed of 1,200 ft. per min. are cut to length through the action of a photoelectric cell through a timing arrangement whereby the shears and a "kick-off" device are operated at the proper instant.

At one of the large steel plants, a battery of soaking-pit furnaces have their covers controlled by photoelectric cells. When the traveling-crane operator desires to open one of the furnaces, he simply projects a beam of light on the corresponding photoelectric cell and the pit opens, thus doing away with the complicated trolley and wire connections otherwise required to connect the cover mechanism with the traveling crane.

In an iron mine plant, whenever a skip goes into the dump, or comes out of it, the hoistman receives a signal by photoelectric means.

The priming equipment of a Toledo company is in the form of a spray-painting booth with apertures through which the lumber enters and leaves. Two sets of spray guns operate inside the booth. As the lumber enters the booth, it trips a small flag which intercepts a light beam, thus causing the first set of spray guns to operate. As the lumber travels forward, the second set of spray guns likewise is brought into play, so that the entire surface of the lumber is sprayed.

A new form of "dye jig" automatically is reversed so that it keeps the material to be dyed moving continuously back and forth through the dye liquid. This material is wound on to a beam roll at each end of the machine. As each roll of cloth gradually is decreased in diameter it finally gets small enough to permit a beam of light to pass and thus cause the reversal of the machine.

Waxed wrapping paper is manufactured and shipped completely imprinted, but in large rolls, and is cut into proper lengths by the automatic wrapping machine, though it is not accurate enough to cut the paper off at the proper point of printing. A small printed spot was placed on the printed waxed paper in register with the design and spaced at regular intervals. The spot casts shadows upon the photoelectric cell to control the cutting-off knives. This is necessary because of stretching and slipping of the continuous roll.

Breaks and "wrap-arounds" cause much trouble in paper manufacture. A photoelectric cell sees the paper break and stops the machine. A knife then rises and cuts the paper free from the roll.

Photoelectric cells control winding reels over a speed control of 20 to 1. Formerly a man was needed to vary the speed and maintain a free loop in the product.

In a photoelectric humidifier, a good measure of moisture is the accumulation on the window pane. Light is reflected through the pane from a lamp to an outside mirror, back into the room and out again, and back through the pane to a photoelectric cell which starts and stops the humidifier.

The roasting of coffee and the baking of bread are controlled by their respective shades which are constantly watched by a photoelectric cell.

Photoelectric cells also regulate the flow of gas in sulphuric-acid manufacture and control shaft revolutions. They do

many other things not herein related, but the foregoing are good examples.

150. Safeguarding.—In the Holland tunnel between New York and New Jersey the presence of excessive smoke or gas automatically starts up the ventilating blowers, while the various tunnel entrances are safeguarded by beams of light which, when intercepted by trucks of excessive height, cause a bell to ring in the police booth.

In the seventy-story building in the Radio City section of Rockefeller Center, New York City, 58 elevators are equipped with "Safe-T-Ray" light-operated devices for guarding passengers from injury hazards of fast-moving door panels. Carried on each car, and serving wherever the elevator stops, the rays are arranged above the elevator-door thresholds at two heights, of 6 in. and 3.5 ft., one above the other, like intangible bars about 2 in. in diameter. The photoelectric cells, through their amplifying apparatus on top of the elevator cab, control the car doors so that upon the presence of a passenger in the doorway they cannot be closed, or if they are closing, the doors reverse and fly open.

A photoelectric unit designed to operate a camera and a flashlight circuit automatically takes photographs of any unexpected visitor to a laboratory. By adding a special chemical to the material inside the flashlight bulbs, the latter were made to explode with a loud noise.

A new device tried out over a stretch of several hundred miles between Berlin and Munich employs a searchlight on the front of the locomotive, from which a narrow beam of light is thrown upward during all the time the locomotive is in operation. A ring of photoelectric cells is located around the searchlight lens. When the train comes to a signal post the mirror thereon reflects the light back to one of the cells, giving a visual signal in the cab, and remains until the engineer acts on it; if he does not respond promptly, the train is stopped automatically.

By means of a light beam and photoelectric cell on a punch press, as long as the operator's hand is in the danger zone, the press cannot be operated.

Other safety devices cause the shutting down of high-voltage apparatus, such as x-ray apparatus, when one approaches too near for safety, and they also stop machinery in some instances.

The photoelectric cell can perceive light invisible to the human eye. Since infra-red rays penetrate fog, there have been a number of suggestions for the safeguarding of ships and aircraft cruising in fog. Langmuir and Westendorp suggested feeding special beacons with 1,000-c current so that they will give a rapidly flickering light. The operation depends chiefly on the fact that the photoelectric cell is thousands of times more sensitive to diffused light than the human eye.

151. Counting.—Vehicles intercepting light beams directed from overhead to photoelectric cells imbedded in the roadbed opposite each end of the ten incoming lanes of the Ambassador Bridge across the Detroit River cause them to be counted and give an indication of the density of traffic and the efficiency with which the tolls are collected.

Butter cartons were sold by weight, and because of the variation of the wax, a 10 per cent allowance was made for overweight to be sure that customers were obtaining the proper number. When counted by photoelectric counters, customers received the correct numbers.

The above examples are but characteristic of the uses of photoelectric counters which are employed in theaters, museums, public buildings, and so forth. In production lines they count motors and other finished articles or machines; rapidly moving, freshly painted articles on a belt or conveyor; red-hot ingots; animals in stock yards, and so on. Thus logs are automatically counted as they rush by at high speed, carried by a stream of water.

A "quantum counter," so sensitive that it can detect the ultra-violet rays from a lighted match some distance away, has been developed by Locher. Connected with its amplifier and a loud-speaker, a candle three or four feet away produces a steady roar. It is so sensitive that it actually counts the number of electrons liberated from the metal. Since each electron requires one quantum for its release, it was given the above name.

152. Sorting and Grading.—Brown or discolored beans are sorted out from white ones by means of an automatic photoelectric bean sorter. The beans are placed in a hopper, pass a patter which adjusts them to the correct position on a drum where they are held by suction, and then they pause a moment while being inspected by the electric eye. The presence of a discolored bean causes a thyratron to actuate a finger which

pushes the objectionable bean into the reject shute. Two hundred of the machines sort a carload of beans a day—a total of 40,000 lb. Coffee likewise is graded by photoelectric cells.

Mail bags are routed and mail is sorted by means of photoelectric equipment. A photoelectric card sorter instantaneously reads cards fed to it and directs them to their proper compartments, combinations up to one hundred million being possible on the small 3- by 3.5-in. cards used.

A photoelectric cell combined with a photometer sorts glow lamps. Bottles of white, green, and brown glass are sorted by the relative amounts of light passed. Almonds are sorted, by size, into three groups. Egg-candling machines grade eggs into various classes. In a test against a professional egg-candler the machine passed a number of eggs that the man rejected. When the eggs were opened they proved to be good. Cigars, tile, vegetables, and so forth, also are similarly graded, as many as a hundred different classifications being possible in some instances.

153. Measuring.—In scales used for automatically measuring the proper amount of sand and cement for ready-mixed concrete, the scale beam is set for the weight desired by means of a poise. Cement is fed into the hopper and, when the proper weight is obtained, the scale beam rises and exposes the light source which energizes the photoelectric cell, thus causing the opening of the control circuit and stopping the supply.

In another form of batch-weighing scale the photoelectric cell is mounted behind a slot in the scale dial and is "eclipsed" when the desired weight of material has been fed into the hopper.

Continuous weighing is accomplished by moving the load to be measured at constant speed over a scale by means of a conveyor belt, the weight of the load being transmitted directly to the end of the fulcrumed weighing beam, causing this beam to swing over the scale of the load indicator at the far or free end, the total weight of the load moved during a given time being integrated over the time of weighing, much as a watt-hour meter adds up all of the instantaneous values of the varying load over a given time interval. By means of an ingenious device involving a photoelectric cell at the free end of the scale beam, electrical impulses are transmitted to the electrical integrator at time rates varying with the load on the scale.

In timing the flight of anti-aircraft projectiles, the light from the muzzle flash causes a spark to jump through a sheet of

paper carried on the drum of a slow-moving Aberdeen chronograph, and the light from the burst projectile at a remote point causes a second spark to jump through the action of the customary relay, being especially adapted to night firing. The photoelectric cell also has been applied to measurements of projectile velocity. When the projectile passes overhead a reduction in the light striking the photoelectric cell is recorded.

Timing races to within a hundredth of a second is accomplished by the report of the starting pistol, picked up by a microphone, starting an electrical clocking device which is automatically stopped when the runner intercepts a light beam at the finish line.

In finding areas under curves, it is customary to proceed by well-known methods of the integral calculus when the equation to the curve is known. In other cases mechanical integration is accomplished by the use of a planimeter—a wonderfully accurate and simple instrument designed for the purpose. In Gray's method, however, the space below the curve on the paper is cut out and light is permitted to pass through the opening. The ratio of this light to that passing through a unit area, as determind by the same photoelectric cell, gives the area under the irregular curve.

The electrochemist employs the photoelectric cell in a variety of ways, one of the most important being the measurement of the acidity or alkalinity of a solution, as further described in connection with colors.

An electric timer has been developed for measuring time intervals as small as five ten-thousandths of a second, as when a golf club is swung between two parallel light beams—one to start and the other to stop the timing.

In the application of the photoelectric cell to the measurement of small displacements, a change in the quantity of light entering the cell changes the photoelectric current which is amplified and measured. The displacement to be measured is made to open or close a slit through which the light is focused on a photoelectric cell.

In the mechanical measurement of yarn levelness as many as 1,000 weighings have to be made to obtain a good value for the coefficient of variation. By causing a magnified image of the yarn to be formed on a slit of adjustable width, the transmitted light falls on a ground glass plate and is diffused over the active

surface where a vacuum photoelectric cell and a Lindemann electrometer[1] indicate the thickness and evenness of the yarn.

In an opacimeter for measuring the opacity or else the transparency of paper and the like, the percentage reading of opacity is in terms of the calibration of the paper itself. The determination of the opacity factor is independent of the color emitted by the illuminating lamps or the color sensitivity curve of the photoelectric cell.

The New York *Daily News*, for example, uses an opacity meter embodying the "photronic" cell, a microvoltmeter and a 100-w bulb, to detect before papers are printed whether the ink will show through and disturb the reader.

Temperatures are measured by means of photoelectric apparatus. These are described under the heading "Recording."

For four and a half days of thick, cloudy weather, the "Mauretania" was navigated by observations of the invisible sun with the aid of measurements taken with the MacBeil infra-red sextant which employs a thermocouple as the radiation-sensitive element, but uses photoelectric cells and electronic tubes to amplify the energy obtained from the thermocouple.

154. Recording.—In the Holland vehicular tunnel connecting New York and New Jersey, photoelectric cells are installed at both the entrances and the exits of the tunnel, the "entrance" cells working the counters forward, as cars pass into the tunnel and intercept the light beams, while the "exit" cells are arranged to operate the counters backward or subtractively, the number remaining on the index at any instant showing the number of cars actually in the tunnel at the moment.

In the recording of smoke density, a parallel beam of light is sent through the smoke or fumes and is reflected back through it along another path to a photoelectric cell, in front of which is a rotating glass disk with a wiper to prevent the accumulation of smoke thereon. The grid of the triode connected to the photoelectric cell is given a positive bias and a recording meter is placed in the plate circuit. By this means, the more smoke there is, the more negative will the grid become, thus causing a deflection of the milliammeter needle.

The temperature indicators designed to replace pyrometers also record, as do other indicating and counting devices. Thus

[1] An instrument used to measure currents and voltages, operating on the principle of electrostatic repulsion.

theater ticket sellers are checked up by light beam counters which also record the number of persons entering a theater.

155. Reproduction.—In sound-on-film reproduction, as in sound moving pictures, wherein a sound track is printed on the edge of the film, light from a lamp shines through an optical system and onto a photoelectric cell, the variations of light intensity through the moving film causing a sound current to flow in the photoelectric cell and through the amplifier to the loud-speaker.

In the optical phonograph call announcer, telephone calls put through on dials to a manually operated exchange are transmitted to the operator in spoken numbers by means of sound-on-film numbers, through the operation of a photoelectric cell as in sound pictures. The spoken numbers are on ten separate films, one for each of the nine numbers and zero, wound on drums which are made to revolve automatically before photoelectric cells when the number is dialed.

Light waves are electromagnetic waves, like radio waves only much shorter. In light-beam transmission, light waves are modulated by the voice so that they really are very short radio waves. When this light falls upon a photoelectric cell connected through an amplifier to a telephone receiver or loud-speaker, the voice is heard just as in the radio. By means of a light-gate arranged to modulate a concentrated beam of the moon's rays, Doherty addressed a nation-wide radio hook-up over them to the broadcast apparatus.

Through the intermediary of the photoelectric cell, printing plates or engravings are made directly from the copy itself. The actual copy, whether it be typed matter, drawing, or photograph, is placed on a drum and revolved past a photoelectric optical system. The dot of variable light reflected from the copy to the photoelectric cell serves to actuate an electromagnetic engraving tool working directly in soft metal such as zinc to produce the final printing plate.

With the Howey automatic photoelectric engraving machine inexperienced office help can produce halftone cuts for black and white reproductions of photographs on the printed page in four minutes at a cost of three-quarters of a cent per square inch. Until now it has required several hours, a complicated acid process and skilled labor to do this same work. Three-color cuts, which formerly needed 36 hours for production, may now be secured with the same machine in half an

hour. While the photograph revolves on one cylinder of the machine shown herein under a beam of panchromatic light, a photoelectric cell scans the area and delivers electrical impulses to the cutting head which rules lines of varying depths on the metal plate mounted on the other revolving cylinder. (*Electrical World.*)

Inventors all over the world are developing "talking books," something on the principle of sound-on-film, except that reflected light may be employed, which will read the day's news aloud, interspersing editorials and news stories with musical numbers, according to *Electronics.*

In the invention of B. L. Green, copy is prepared on a typewriter in the usual manner, but it simultaneously writes code characters under the usual characters. The typewritten matter with its code characters then is fed to a linotype machine where the code characters are scanned by a photoelectric cell which controls the type matrices, thus dispensing with the linotype operator.

Photoelectric cells also are employed in automatic weaving.

156. Detection and Inspection.—A red light flashes in a bowling alley when a bowler's toe passes to or beyond the foul line, due to a small beam of light focused across the alley very close to the floor. Due to the time lag in the relay, the swift passage of the ball does not operate the signal.

A yeggman unknowingly obstructs an invisible light beam and an alarm is sent to a switchboard.

A photoelectric detector has replaced workmen who formerly watched for breaks in paper during the process of drying on paper-making machines. When a break appears, an audible signal is given or the machine is automatically stopped.

In a car-dumping installation, an empty car traveling down the return track cuts off a beam of light, thus causing the relay to ring a bell to notify the operator when the car has reached the predetermined point where the car-retarding mechanism should be operated.

In an electronic smoke detector or inspector installed in a number of power plants, a photoelectric cell is installed near the bottom of the smoke stack. Opposite it, across the stack, is an ever-burning electric light. If a cloud of black smoke, resulting from careless firing, starts up the stack, the change in the amount of light reaching the photoelectric cell causes a switch

to be operated and the big blowers to be started. These detectors work day and night. They also give alarms and keep records.

The Rentschler burglar alarm employs both infra-red and ultra-violet light beams, both of which are invisible. The interception of either of these beams causes the alarm to be given.

Almost invariably counterfeit stock certificates are printed on a slightly different thickness or stock of paper which is declared as "doubtful" by a photoelectric unit when compared with an original certificate.

A photoelectric cell continually watches the light beam from a reflecting galvanometer forming a part of a seismograph used in recording earthquakes, causing an alarm to sound when the light beam moves with the deflection of the galvanometer's mirror.

Photoelectric cells have been used in connection with color phenomena in the fluorescence and phosphorescence of substances when excited by ultra-violet light. Many stains otherwise indistinguishable thus can be detected and identified. The use of fluorescent substances in ink and paper as identifying media also has been proposed, to avoid possibility of counterfeiting.

The illumination produced by fires causes photoelectric units to send in alarms and start sprinkler systems. In the demonstration of Chubb's fire scanner, four flames were lighted on a screen, the scanner was set in motion, and as it came in line with each fire, it stopped, aimed a stream of water, and then, the flame extinguished, went to the next fire.

Jail deliveries are prevented by photoelectrically controlled guns.

Collapsible metal tubes used for creams, tooth pastes, and so forth, are inspected for air holes by whirling them rapidly over a light in front of a photoelectric cell. If any light leakage occurs, the tube is marked and thrown aside.

In the Firestone inspection device, any object shiny enough to reflect light is revolved under the lens of a microscope, the reflected light passing through the microscope to a photoelectric cell. Flaws or cracks as small as one ten-thousandth of an inch alter the quantity of light sufficiently to cause a change in the photoelectric current which, in turn, causes a gaseous-discharge tube to operate and hold the discard path open.

Most bottles are blown by automatic machines and strains often develop which result in a weakened product, being susceptible to breakage if brought into hot water or other hot liquids.

Prisms in connection with photoelectric cells are employed to indicate the amount of strain in the glass vessels under test so that such flaws may be found automatically.

In testing raw silk, samples are wound on a block board with about 100 threads to the inch. When the thread is not uniform in size, the fine and coarse parts show up as light and dark bands which are inspected by a photoelectric cell as the board is carried at constant speed past the light by which records are made by a curve-drawing wattmeter.

Electrical apparatus and parts automatically are tested through deflected needles over holes or slots and light beams from galvanometer mirrors, after the general manner described in Chap. XVIII. Tietz and Paulson have described a number of methods in a well-illustrated article in the January, 1932, number of *Electronics*.

157. Aids for the Blind.—By means of a photoelectric device invented by Fournier and Auger, a note is heard in a telephone receiver worn by a blind French soldier, whereby he can distinguish not only daylight from darkness by the change in the pitch of the note, but can locate a sheet of light-colored paper on a table top; locate dark- or light-colored furniture; distinguish between persons who are lightly and darkly dressed; find an open door or window in a shaded room, and so forth.

The "talking books" referred to in Art. 155 should be a great boon to the blind.

In the Thomas apparatus for the blind, light from a projector illuminates an area corresponding to only one letter at a time on a printed page from which it is reflected onto a series of 42 photoelectric cells. Through the associated amplifiers and a series of electromagnets, sharpened plungers are raised above the surface of a "feeling block," whereby the black portion of a printed page is translated and enlarged so that it may be "read" by the thumb.

158. Photoelectric Cells and Color.—In most of the foregoing applications of the photoelectric cell in industry, actual color is of little consequence so long as sufficient light reaches the cell to cause it to operate a meter or a relay through the associated circuits, although it is desirable that the color response of the cell and the predominating colors of the light source shall correspond in order that the maximum sensitiveness of the photoelectric equipment may be obtained.

True color discrimination has to do with the quality of the reflected and transmitted light, as in the photometry or measurement of lamps emitting and transmitting light of different hues and intensities through their envelopes. Color photometry or colorimetry is the measurement of the quality of direct, transmitted or reflected light and it is in colorimetry that the photoelectric cell finds its most exacting application.

The eye cannot distinguish between spectral and mixed or compound colors, while the photoelectric cell responds to every spectral color and even may be made to respond to individual wave lengths of light of such small intensity that the eye cannot detect them with the aid of a spectroscope. It is this analytical and color sensitiveness of the photoelectric cell that makes it so superior to the eye in color measurement and comparison. Furthermore, the eye almost invariably suffers to some extent from color blindness.

The usual method of preparing a photoelectric unit for color measurement and comparison is to select a cell having high sensitiveness throughout the whole visible spectrum and then cutting it down by means of filters and voltage adjustments so that it will fit the normal sensitivity curve. This is a rather difficult process, however, and the difference between cells prepared in the same manner, due to the elaborate sensitizing processes used to make them color-sensitive, does not tend to make the task easier.

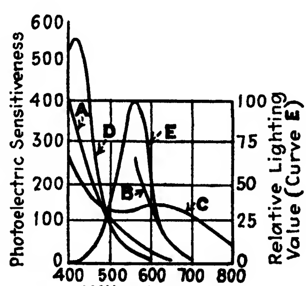


FIG. 210.—*A*. Caesium on silver, 45 v. *B*. Caesium on silver, 90 v. *C*. Caesium on copper. *D*. Potassium hydride. *E*. Normal visibility curve.

Figure 210 shows a few curves, compiled from data by Hess in the August, 1930, number of *Electronics*, for various types of cells, with the normal visibility curve *E* added on a different scale. It also shows that the caesium-on-copper cell *C* sensitiveness extends into both the infra-red and ultra-violet regions, whereas the potassium hydride cell *D* is unsuitable for the replacement of the human eye in color photometry since it loses all but a very small portion of its sensitiveness at the very place where the eye is most sensitive. Hence filters would be of no avail in this case. Nevertheless, it is very sensitive in the violet region. Substantially the same remarks apply to the

caesium-on-silver cell *A* shown at 45 v. These are not criterions for other types of cells, but merely illustrate the principles involved. In contrast to these curves, Figs. 185 and 187 show curves very similar to the normal visibility curve.

When a photoelectric unit once has been adjusted and fitted to the normal visibility curve, if the mixture of transmitted or reflected colors consists of the two colors red and bluish green, the photoelectric cell will respond most intensively only to these colors. The same holds for orange and greenish blue, yellow and blue, violet and greenish yellow, and green and crimson rays; yet the eye transmits these complementary colors to consciousness as white in every case.

As a result, colors now are matched and processes are controlled through color variations with far greater precision and ease than possibly could be done with the unaided eye. It is obvious that the method of color definition described in Art. 128, wherein are shown a few points which might be measured for a given shade of green, is very exact and color accurately may be reproduced by it from a filed record of the wave lengths and intensities at the points on the curve in Fig. 176. A photoelectric cell corrected to the visibility curve by the methods above described actually responds to every wave length present in such a curve, whereas the eye merely notes that the color is a shade of green.

While two colors that appear identical in color to the eye when viewed under one illuminating source may appear unlike under different illumination, when the contours of the spectral reflection or transmission curves of two materials are identical, the materials will appear alike in color, regardless of the spectral composition of the light under which they are compared.

In matching colors or shades, light reflected from a given sample of material may be measured by means of a photoelectric cell, a triode and a meter in the usual manner.

159. Color Matchers.—There are two general methods of precision color matching, namely, the substitution and the balance methods.

Wilson, Hein, and Hitchcock have described in the November, 1932, number of *Electronics* a portable color matcher, independent of daylight or artificial light, wherein a tricolor filter permits transmission of one of the three color bands—red, green, or blue. The photoelectric tube employed has a special color characteristic to give the best operation with the lamp source. By means

of a lens and a mirror, the light rays are brought to the sample through a diffusing transmitting medium. A white integrating cylinder brings the mixed rays to the photoelectric tube.

The device is provided with a sensitive control which is adjusted until a zero indication is obtained on the meter with the standard sample color for each of the three filters. Then the test sample is introduced, when the direction of the needle from zero indicates whether the tested sample is "lighter" or "darker" than the standard.

In principle, to the standard, in which 99 per cent of the diffused reflected light is red and 0.6 per cent is blue, the red filter is applied and the sensitivity control is turned down until a zero indication is obtained. Then a test is made with the blue filter, the sensitivity control being turned up until the meter again indicates zero. It is evident that 0.6 per cent in the blue now has as much effect on the circuit as the 99 per cent of the red had on the circuit when the red filter was used.

For simplicity, let it be assumed that 99 per cent of the diffused reflected light from the sample also is red but that 0.4 per cent is blue. When the standard is removed and the sample inserted with the blue filter still in position, the zero remaining set for 0.6 per cent blue in the standard, there will be a marked change in the meter reading, showing that the sample reflects less blue light. The green filter is used in a similar manner.

Thus the colors of plates, fabrics, dyed material, print samples, semi-fluids, pastes, powders, foodstuffs, and so forth, may be matched.

In the Sheldon "Coloroscope," two photoelectric cells form two branches of a balanced circuit, much as the standard resistance and the resistance to be measured form two branches in the well-known Wheatstone bridge (Fig. 201), that is, they are connected to an indicating meter in such a manner that when both are receiving the same amount of light, they will hold the pointer at zero. The resistances of the photoelectric cells change with changes of light intensity, so that if one or the other receives more light, the needle will be deflected to the side registering the stronger radiations.

A standard color, as a sample of dye selected as the standard, is placed in the apparatus in such a manner that light from a single source is reflected from it into the cell. The needle next is brought to zero by a dial control. The sample to be compared with the standard next is inserted and the deflection of the needle

noted. If there is a difference of shade, even though it be too slight for the human eye to detect, the difference will be indicated by the needle.

The weave and surface glare of textiles and other materials are eliminated by placing the color to be compared in a revolving head and reflecting light from the single source from them onto the photoelectric cell. A calibrated iris diaphragm allows the color differences to be expressed in per cent of total light.

Among other devices on the market is the "color comparator," for comparing similarly colored liquids or opaque materials, reported to measure within 0.05 per cent, or about forty times more accurately than the human eye. It measures the relatively total light transmission over the visible range when similarly colored liquids are placed in standard glass-cell containers.

Such devices show immediately whether a misdye can be corrected by additional dyeing. In the absence of a match, it indicates in terms of primary colors how corrections should be made. It also enables the operator to calibrate the coloring of each dye and to measure the amount of dye needed.

The use of color matching devices in blood analysis and other physiological analysis, and in chemical analysis depending upon the detection of color changes, is important. Thus it is possible to determine with great accuracy whether a solution is alkaline or acid or whether these two chemical conditions neutralize each other. To cite a simple case, the automatic mixing machinery in industrial chemical plants may be automatically stopped when an alkaline or acid neutralization is achieved in the flow of different chemicals, or the associated apparatus may be made to control or stop the addition of the neutralizing agent.

In one instance, light shines through samples of water from the supply to a photoelectric cell. The density of color obtained in the test regulates and activates the apparatus furnishing liquid chlorine to the water supply.

The G. E. photoelectric recording color analyzer automatically plots a continuous color curve on a liquid or solid sample for the visible range in a few minutes with sufficient accuracy to check with Bureau of Standards data on a color filter and is said to be so constant as to retrace a curve on a sample without appreciable widening of the pen line.

A very large number of practical applications of the principle are possible.

CHAPTER XX

CATHODE-RAY TUBES

It has long been desirable to know the instantaneous magnitudes of current strength and voltage in connection with transient and cyclic phenomena, especially in complex electric circuits. The electromagnetic oscillograph, wherein a loop of current-carrying wire supporting a minute mirror is sustained under tension in a magnetic field, was developed for this purpose, but it falls far short of being sufficiently fast for many purposes. With the advent of the modern cathode-ray oscillograph, however, even very high-frequency phenomena may be observed as graphs in an ordinary lighted room by a class or other group, and photographic records may be made of extremely brief transient phenomena. But this is only one of the applications of the cathode-ray tube discussed in this chapter.

160. General Principles.—In the types of electronic tubes and apparatus thus far discussed, excepting in Art. 53 which relates to this subject, only the variations in the numbers and speeds of moving electrons have been considered. A pen-and-ink sketch drawn by an artist may consist of a series of lines wherein shades are produced by lighter or heavier lines, as by varying the pressure on the pen, much as photographs are reproduced in halftones as a series of dots of varying shades. This is the equivalent of varying the electron current in an electronic tube, as in a glow lamp, to produce the varying degrees of light intensity required in television reception as the perforated disk and optical system project the varying light beam on to a screen in the form of a series of parallel lines of light of constantly varying intensity, drawn so rapidly across the screen that a motion-picture effect is produced.

The electron stream or beam, or cathode ray, also may be bent or deflected upon a fluorescent screen, usually of willemite or calcium tungstate, placed at one end of the tube, either by an electrostatic field produced by applying potential to parallel non-magnetic metal plates, preferably placed inside the tube, or

by magnetic fields produced by electric currents in coils outside the tube.

Deflecting coils are very convenient when the currents are sufficiently strong for the purpose, while deflecting plates are particularly advantageous for circuits of very high impedance. The cathode-ray tube consumes no power due to its deflecting plates, this being very desirable in radio work where the power output is very limited and the frequency is very high. When only one pair of deflectors is employed the cathode-ray tube will draw lines of varying intensity, as required in television, the intensity of the lines in their various positions varying with the current strength in the receiver as produced by the varying light intensity received in the photoelectric cell at the transmitting station. When a single pair of deflectors is used, the cathode-ray tube also will draw lines whose lengths represent the maximum or peak alternating voltages, as the beam moves rapidly to and fro on the screen.

When two pairs of deflectors are employed at right angles to each other, however, the cathode-ray tube will draw sketches or graphs in light showing the relations between two varying quantities at all instants. Hence the cathode-ray tube is essentially a writer or sketch-drawer whereby it is possible to obtain writings or graphs upon a fluorescent screen for observation, or upon a photographic plate or film for recording and preservation.

Fundamentally, this is the principle of Gray's telautograph, or writing telegraph, an old and long-used device with many applications, wherein a stylus at the transmitting station is connected through a pantograph arrangement, similar to that used for the mechanical copying or enlargement of drawings, with variable resistors, in such a manner that when the stylus is moved upward on the paper, one of the resistances will be varied and when moved horizontally the other resistance is varied. Hence, when the stylus moves diagonally, both resistances are varied, each resistance being varied in proportion to the distance the stylus has been moved in the direction affecting that resistance.

At the receiver there are two solenoids or other electromagnetic devices, connected by wire with the transmitting-resistance circuits, which move a pen over paper. Each solenoid moves the receiving pen in each direction, upward and horizontally, in proportion to the change in the resistance in series with it at the transmitter. Hence, when the transmitting stylus is moved

upward on the paper, the pen at the receiver also moves upward on the paper. The same holds for the horizontal movements. Therefore, when the stylus at the transmitter is moved diagonally over the paper, the pen at the receiver also is moved diagonally over the paper, thus always faithfully reproducing in ink the makings of the stylus at the transmitter. In this manner sketches and charts, as well as writing, are reproduced at remote receivers. But shading cannot be obtained in this manner.

The cathode-ray tube with two pairs of deflecting plates not only has replaced the equipment of the telautograph receiver in DuMont's cathautograph, but it also may be made to produce shades, as stated in the foregoing. By the use of special salts in the fluorescent screen at the end of the tube, the written words do not fade out for nearly 30 sec. This permits about ten words to be written and observed on the fluorescent screen of the cathode-ray tube at one time, the first word written fading out as the last word appears on the opposite side of the screen.

161. Development of the Cathode-ray Tube.—The cathode-ray tube has long been known as the Braun tube, for it was Braun who, in 1897, first put these tubes to practical use, although three-electrode tubes, wherein one electrode electrostatically influenced the electron stream, had been constructed several years previously. Braun's tube employed a cold cathode and required rather high voltage for its operation. In 1905, Wehnelt constructed a hot-filament tube which operated on a 220-v power circuit. Since that time the cathode-ray tube has undergone much development.

Modern cathode-ray tubes have been developed so far as to be demountable, as in those developed by DuFour, Norinder, Rogowski, and others. In these the photographic film is placed inside the tube; the tube then is reassembled, and finally exhausted by a pump or pumps kept in constant operation. In most cases, however, the writings are directly observed on the fluorescent screen, or they are photographed by placing a camera above the screen, or, where the writing is rather faint or the transient phenomena very brief, the photographic film is placed directly upon the outside surface of the tube above the screen.

A standard cathode-ray oscillograph tube consists of a sealed-off glass tube containing a cathode, an anode, and one or more pairs of deflecting plates. Deflecting coils generally are placed outside the tube, as also are the deflecting plates in many

instances. When such coils are used, they are set at right angles to the positions that otherwise would be occupied by the plates. This is illustrated in Fig. 211, wherein a pair of deflecting plates is shown with a pair of deflecting coils or magnets, the position of the deflecting plates, in case the coils were not used, being shown in dotted lines.

With no voltage impressed upon the deflecting plates, or with no current flowing in the deflecting coils, the electronic beam passes upward from the cathode through the hole in the anode and thence through the center of the tube, striking the center of the fluorescent screen at the top where the electronic bombardment produces a bright spot of blue light. When the deflecting elements are variably energized, however, the point of light traces an image of the screen as above described. The axes x and y, Fig. 211, may be obtained by successively suppressing each pair of

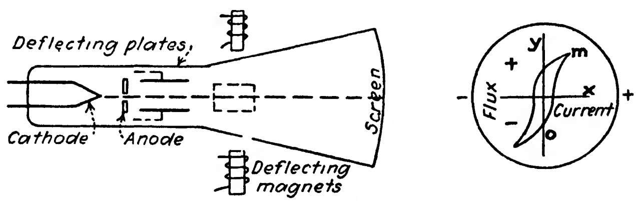


Fig. 211.—Simple principle of the cathode-ray oscillograph.

deflectors so as to cause the point of light to write vertically or horizontally, as desired, only one, if either, of the axes commonly being employed.

The graph shown on the screen in Fig. 211 is the well-known magnetic hysteresis loop. When a current flows in a coil linked with a closed iron magnetic circuit (Fig. 65), the magnetic flux density in the iron increases to a maximum as the current strength is increased to a maximum. When the current strength is zero, the magnitude of the magnetic flux is negative, as represented by point 0. When the current strength is a maximum, as represented by point m, the magnetic flux also is positive. As the current strength is decreased and the direction of the current is reversed, and its strength increased in the negative direction, the magnitude of the magnetic flux still lags behind that of the current strength due to the "hysterical" effect in the iron, somewhat analogous to friction between the atoms.

The atoms do not naturally return to their normal neutral positions in closed iron magnetic circuits, but have to be forced

there by the magnetizing magnetic flux caused by the current. Hence, if any point on axis x represents the current strength at any instant and any corresponding point on axis y represents the magnitude of the magnetic flux in the iron at the same instant, the relations automatically may be pictured on the screen in the form of the hysteresis loop, the area of which represents the energy loss per cycle through heat in the iron.

When the current starts to flow the first time, the magnetic flux is zero in the iron. Thereafter it has the various magnitudes shown in the following cycles. The value of the maximum magnetic flux in the iron may be computed.

Cathode-ray tubes of this general character, in different types and sizes, are now on the market at relatively low prices, suitable for a wide range of experimental and laboratory applications, which may be used as voltmeters, ammeters, or resonance indicators, and so forth, as well as to demonstrate the basic principles of the cathode ray. They may be obtained with or without deflecting plates, inside or outside. Such tubes must be calibrated by marking points on the screen, or on a scale adjacent thereto, as by means of a battery and a voltmeter. Then, if an alternating voltage is applied to the plates, the farthest point reached by the beam will indicate the maximum or peak voltage of the wave. Calibrations likewise may be made for current strengths when deflecting coils are used.

In one type of low-voltage tube, normally operated at 350 v, wherein the pressure of argon gas is employed for focusing purposes, the amount of light emitted by the fluorescent screen under the electron-beam bombardment is limited but very useful for the observation of repeating low-frequency phenomena.

It is desirable that the electrons pass through a hole in a shield to prevent heavy positive ions formed near the plate from bombarding the coated filament, when filaments form the hot cathodes, and that the filament and plate be enclosed in a narrow glass tube to reduce the space in which ionization may take place in the gas, which reduces wall charges and helps to produce a narrow beam.

162. Accelerating the Electrons.—The anode accelerates the electron stream and causes it to bombard the fluorescent screen. The velocity of the electron stream is equal to 60 million times the square root of the accelerating (anode-to-cathode) voltage. Since high electronic velocities are required to produce strong

fluorescence when phenomena of extremely brief duration are to be observed or photographed, accelerating voltages of the order of 60,000 v sometimes are employed in cold-cathode tubes to give the electrons a velocity of about 1.5 billion centimeters, or about 93,000 miles, per second, which is about half the velocity of light.

The selection of the accelerating voltage in a cathode-ray tube is a compromise since the stronger is the electronic bombardment, with its consequent increase in intensity of light on the screen, the smaller becomes the deflection of the ray with given deflecting voltages or currents. This sensitivity of deflection, which can be increased only at the expense of illumination on the screen, varies inversely as the square root of the accelerating voltage.

163. Two-anode Tubes.—In order that the electron beam may be controlled better, a second anode, at much higher potential than the first, is employed in some tubes, the first anode giving the beam the initial acceleration and the second anode greatly increasing its speed.

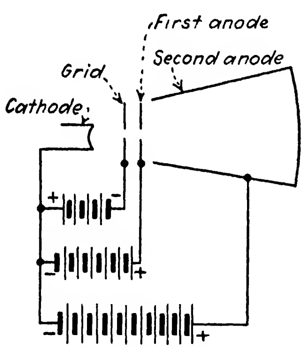


FIG. 212.—Schematic principle of grid and two accelerating anodes.

When early attempts were made to build experimental cathode-ray tubes for voltages exceeding 250,000 v, the electron beam was in evidence even when the cathode filament was not heated, this being referred to as a "cold-cathode" effect. It was found that this effect could be overcome by dividing the voltage between different pairs of tubular electrodes, thus dividing the tube into sections, each of which could withstand 300,000 v. On this basis, a three-section cathode-ray tube was built for 900,000 v. This cascade or multisectional system is applied to x-ray tubes and was developed by W. D. Coolidge.

The cathode-ray tubes herein discussed have both anodes included in the same tube section.

164. Tubes with Grids or Control Electrodes.—In the visual observation or photographic recording of transient phenomena, as lightning discharges through a lightning arrester, or line surges caused by lightning, or otherwise, wherein the phenomena to be observed or photographed are but of a few millionths of a second's duration, it is important that the tube should function

at the same instant that the transient phenomenon starts. In such cases the film often is especially sensitized. For this purpose a grid or control electrode is employed which holds back the discharge of the beam through a negative bias until the transient phenomenon starts, and then the tube functions in the usual manner. The grid also is used to stop the discharge. Biasing the control grid also provides a simple means of timing the exposure and obviates the fogging of films.

Figure 212 shows diagrammatically a cathode-ray tube with a second anode and a grid.

165. Hot-cathode Tubes.—In this general type of tube it is important that the construction be such that interference with the electron beam by the magnetic field caused by the filament current be avoided.

Two improved high-vacuum, hot-cathode cathode-ray tubes of the sealed-off type, both being heated by alternating current, were described in the November, 1931, and in the May, 1932, numbers of *Electronics*, the former by Zworykin and the latter by Metcalf.

In the first type referred to, a coiled tungsten filament is mounted within a nickel sleeve having a cup-shaped depression in one end, said depression being coated with barium-strontium oxide. The cathode is almost completely enclosed in a cylindrical control electrode, the emitting end of the cathode being located just opposite a small hole in the face of the control electrode, and all three elements are assembled on a four-wire press.

Between the fluorescent screen, which is about 7 in. in diameter, and the middle of the first deflecting elements, which are thus located near the first anode where the electron velocity is small, the inside of the bulb is silvered to form the second anode to give the final acceleration to the electron beam, said silvering being in contact with a lead-in wire. The fluorescent screen is made slightly conductive and is connected to the second anode to prevent a charge accumulating on the screen and repelling the electron beam. The glass at the screen is about $\frac{1}{16}$ in. thick.

The focusing is said to be accomplished apparently by an interaction of the electrostatic field between the first and second anodes and the magnetic field of the electron beam; it does not depend upon the presence of any residual gas, being better for higher vacuum. It is stated that the focusing is very positive

and can be simply controlled by adjusting the ratio of the two anode potentials.

It also is stated that this tube has been successfully used for television reception without distortion, even for strong contrasts of intensities, the first anode potential being about 400 v, the second anode potential 2,000 v, both positive, while that of the control electrode is 45 v negative, although voltages up to 15,000 v may be used. The second anode current and the intensity of the spot can be controlled by varying the potential of the control electrode without affecting the deflection of the beam, since the controlling potential is relatively small. Either external deflecting plates or coils may be used.

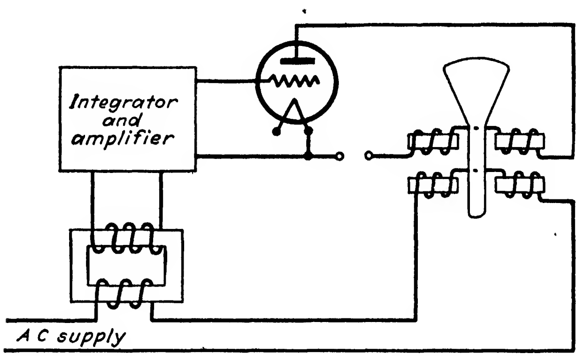


Fig. 213.—Schematic circuit for obtaining the magnetic hysteresis graph.

It is further stated that by a proper dimensioning and spacing of the electrodes, the spot on the screen becomes very brilliant, the recording with this tube being almost as good as when the photographic film is placed inside of it. Characteristics of lightning arresters have been studied visually, even though the duration of the complete cycle was less than 50 microseconds. The second anode potential employed in these observations was only 3,000 v.

The tube described by Metcalf also has a metallic coating and is provided with two pairs of internally mounted deflecting plates, but deflecting coils may, of course, be used. A resistance voltage divider is used to obtain voltage taps for both the cylinder and the grid voltages. With an accelerating voltage of 1,000 v, a sensitivity of 23 v per in. may be obtained, that is, a deflection of 1 in. may be obtained with a deflecting voltage of 23 v, the brilliancy of the writing at this voltage being sufficient for obser-

vation in normal daylight. The voltage sensitivity is sufficient for use on 110-v circuits with high accelerating voltages. It allows observation in full daylight of repeating phenomena at 300 million, and photographic recording of single transients up to half a million, cycles per second.

The circuits in Figs. 212 to 214 are approximately reproduced from the article by Zworykin. For the production of the hysteresis loop in Fig. 211, the circuit in Fig. 213 may be employed.

Some of the repeating phenomena require the deflection of the beam at constant speed in order to provide a linear time axis. This may be accomplished with the separate sweep or deflecting circuit in Fig. 214, although there are other circuits. In this method, a voltage which increases linearly with time to its maximum value and then quickly falls to zero and again increases

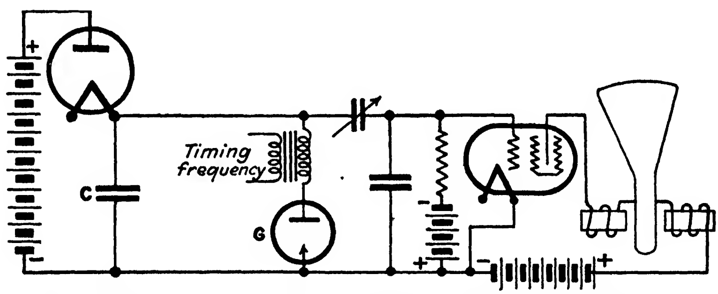


FIG. 214.—Circuit for linear time coordinate to observe repeating phenomena.

to its maximum value, over and over, is applied to one of the deflecting plates, thus providing a linear time axis for the pattern on the screen, resulting in a curve showing directly how the voltage applied to the other pair of deflecting plates is varying with time.

Referring to Fig. 214, the condenser C is charged through a vacuum tube operating beyond the saturation voltage, so that it will act as a constant current-limiting device to make the charge of the condenser increase linearly with respect to time, that is, to make its time rate of charging constant, the resulting potential being applied to the screen of a screen-grid tube (or to the grid of a triode in some cases) the plate current of which supplies the timing current to the deflecting coils of the cathode-ray tube.

By means of a controlling impulse sent through the transformer in series with the glow tube G the condenser is discharged

therethrough and the process is repeated. In this manner timing potential causes the beam to sweep across the screen in a straight line at a uniform speed, in the same time required for the potential on the other set of plates to pass through one complete cycle. Such timing circuits may be regarded as oscillators having the required wave form for the purpose. Frequencies as high as 50,000 c per sec. have been used in such circuits.

166. Applications of Cathode-ray Oscillographs.—The following information is gathered from the two articles referred to above, as well as from other sources, without regard to the type and without any comparisons, the object being to show what may be accomplished in general.

Almost any effect may be converted into an electrical effect which can be electrically indicated and recorded on an electrical instrument calibrated in terms of the original effect, as temperature, pressure, speed, and so forth, by means of pyrometers or photoelectric cells for temperature, the change of resistance in a carbon pile with corresponding changes in pressure, and so on. Thus a gas-engine indicator with a cathode-ray tube gives a visual indication as well as a photographic record of the pressure within a cylinder at any instant.

Examples of industrial applications are the study of phase relations in alternating-current circuits, distortion in audio-frequency amplifiers, mercury-arc rectifier performance, voice modulation, circuit-breaker functioning, power phase distortion, vibration, the recording of transmission-line surges, testing of transformer iron, analysis of commutation on direct-current machines, and the measurement of power factor in high-impedance circuits.

When only a portion of the writing is to be studied, the beam may be deflected entirely off the screen so that only the portion under observation will remain in an enlarged form. It is customary to make visual observations prior to photographic recording, in which a moving picture camera also may be used.

The time lag of the light on the screen is made very small so that single transients having frequencies of several million cycles per second may be observed. In such cases the anode voltages must be adjusted so that a good compromise between electron speed and beam deflection shall be obtained. In the cases of recurring phenomena, however, where the writing repeatedly is traced over the same path, the anode voltage may be made

smaller, thus permitting greater deflection. Writing speeds of more than 100 km (62.1 mi.) per sec. may be obtained with the oscillographs described.

In sound-on-film recording with a cathode-ray tube, the fluorescent area is made of linear form by electrostatic screens, and either variable intensity or variable length can be used, the tube being so sensitive that it can be connected directly to the microphone.

A cathode-ray tube also has been reported wherein the rays are produced as an inertia-free compass and inclination indicator for aerial navigation, the earth's magnetic field holding the beam in one direction so that any displacement of the tube becomes visible.

Low-speed cathode rays have been used to produce artificial aurora.

The cathode-ray tube enables the chemist to photograph the cause of a reaction which is too fast to be followed by the eye, and permits the constant checking of audio-frequency wave form required in many precise measurements on solutions and gases.

By amplification with a resistance-coupled amplifier, muscle and nerve currents are recorded by a cathode-ray oscillograph. It is stated that they also can be heard in headphones, "this method being sensitive enough to detect the current produced when the subject merely *thinks* of a muscular action, the muscle remaining apparently at rest."

DuMont's cathautograph may be operated over radio circuits by modulating two separate tones on a single carrier wave, each tone being rectified at the receiver and used to operate a set of deflecting plates. Suggested applications are the communication between small vessels at sea not carrying a licensed operator, and land station; between airplanes and ground stations; between police department and radio-equipped cars; noiseless instructions to broadcast artists; and so forth.

167. Lenard-ray Tubes.—As stated in Art. 53, the early investigators could not force electrons through transparent bodies, apparently because of the tubes and voltages employed; however, this is done in modern tubes at high voltages. An improvement was made by Eisenhut in 1921, by the use of a hot cathode which reduced the cathode-potential fall and increased the efficiency of the tube. Other improvements were made by Coolidge, notably a support for the metal-foil window and a

tubular shield connected thereto through which the electron beam passed, thus permitting the use of very high voltages with the resulting increased electron speeds. By connecting two or more single sections in series, as described in Art. 163, voltages up to a million volts, preferably obtained from x-ray voltage generators, may be used.

Aluminum foil, glass, and cellon are used for Lenard windows. In a window developed by Slack, the tube is worked to a definite thickness and a bubble, only 0.0002 in. thick, is formed inwardly by sucking on the opposite end, thus making the bubble (Fig. 215) an integral part of the tube. Although so delicate that a touch will destroy the bubble, the tubes are more practical than the metal-foil windows previously employed, only about 30,000 v being required to pass electrons through the glass window in practical operation, as compared to about 70,000 v for the metal

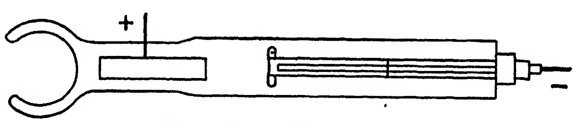


FIG. 215.—Lenard-ray tube.

foil. Mechanical protection for the bubble is provided, although, since it extends inwardly, there is not much danger of its being broken. Electrons accelerated by about 20,000 v cannot pass through the window but heat it through bombardment. With 100,000 v, however, the electrons go through the window with very little loss of speed, and when they do not go through they eject secondary electrons from the outer surface.

Referring to Fig. 215, taken from an article by Dennington in the September, 1930, number of *Electronics*, from which much of the foregoing and following information was gleaned, the electrons from the hot cathode are forced through the hollow anode and through the bubble window. Materials placed about 1 in. away from the window receive the impact of the electrons.

In another form of Lenard-ray tube, suitable for potentials up to 80,000 v and current up to 2 ma., and which it is stated can be left in operation all day without attention, the emission window was 4 by 6 cm and consisted of a cellon sheet 0.016 mm (0.0006 in.) thick, with a reinforcing supporting structure of a fine-mesh metal screen and a grillwork of small edgewise steel

bars. It is claimed that such a window passes 60 per cent of the electrons with undiminished speed and that more than 200 records were made through it without damage of any kind. Investigation on traveling waves with the tube used as an oscillograph gave very clear records in spite of the tremendous writing speed of 3,000 mi. per sec., the durations of such readings being only 1-billionth of a second. It is stated that this oscillograph is much smaller and therefore much more portable than the former (ordinary) glass type.

A small Lenard-ray tube operating at 70,000 v from a 110-v power supply has an aluminum-foil window through which the rays pass to the air, the tube being only 12 in. long with a bulb 3¾ in. in diameter which is mounted on a transformer case 8 by 6 by 10 in. long. The rays, which can be seen in subdued light as a pale haze surrounding the window of the tube, are quickly absorbed and stopped by the air, objects to be rayed being placed within a fraction of an inch from the window.

Maximum writing speeds up to one-quarter of the speed of light have been reported.

168. Effects of Lenard Rays.—Investigations of the actions of Lenard rays on various inanimate and animate objects have been made, notably by Long and Moore, and by Coolidge and Moore. Electron speeds of approximately 125,000 mi. per sec. were employed. Diamonds show fluorescence while being rayed but no phosphorescence or change of color thereafter. Linseed and prilla oils become almost crystal after exposure. The effect on selenium is similar to that of light but more rapid. Sodium chloride (table salt) changes to yellow—about the color of its flame spectra—on long exposure. Likewise potassium chloride changes to purple and caesium chloride to blue. Small insects, fruit flies, and living cells are killed by the rays.

The effect of Lenard rays upon insulating oils is similar to that produced by high-voltage stresses continued over a long period. Hence they have been used for probable life tests on cable insulation.

The showering of high-speed electrons into chemical substances in some instances causes polymerization—an instantaneous molecular readjustment—or decomposition, and so may become very important as a method of preparing certain chemical compounds.

One of the dangers from using Lenard-ray tubes is that they produce x-rays if they strike any part of the hollow anode, but this may be guarded against by shielding the tube with sheet lead, since the heavier the atoms in a material the more easily are the rays stopped. That is one reason why aluminum windows are employed since the light aluminum atoms do not so readily stop the rays.

CHAPTER XXI

INVISIBLE LIGHT

All radio, heat, visible- and invisible-light rays, x-rays, and gamma-rays are electromagnetic rays, supposedly consisting of waves, since all have wave lengths which become progressively shorter in the order given when infra-red rays are classed with heat rays. The wave lengths discussed in the present chapter are those which keep us warm, permit us to see beautiful scenes and objects in all their colors, and those which redden and tan our skins and are beneficial to our health, if not misused, the wave lengths extending between those of radio and of x-rays. These are the invisible infra-red, the visible, and the invisible ultra-violet regions of the solar spectrum.

169. The Infra-red Regions.—The reader is familiar with the heat developed by the "burning lens" which concentrates the sun's rays on a small area. In 1800, Herschel referred to this and told of some of his observations and experiments wherein he used various combinations of colored glasses in viewing the sun through large telescopes, with the obvious intention of preserving his eyesight. He said: "What appeared remarkable was, that when I used some of them, I felt a sensation of heat, though I had but little light; while others gave me much light, with scarcely any sensation of heat."

Herschel separated sunlight into its spectrum by means of a prism and measured the relative heat of each color of light by noting the increase in temperature during 10 min., as measured by a thermometer with its bulb placed in said spectrum. The results were: Red, 7 deg; green, 3.25 deg; and violet, 2 deg. He further stated: "If the power of heating, as we now see, be chiefly lodged in the red-making rays, it accounts for the comfortable warmth that is thrown out from a fire when it is in the state of a red glow . . . May not this lead us to surmise that radiant heat consists of particles of light of a certain range of momenta, and which range may extend a little farther on each side of refrangibility, than that of light?" (Light was supposed to consist of particles in those days.)

The wave lengths of the infra-red region of the solar spectrum are shorter than those used in radio but longer than those of the visible red. The heating effect of the infra-red rays is due to absorption of their energy by the bodies upon which they fall. Hence the term "radiant heat." The wave lengths of greatest penetration appear to be at or near the dividing line between the visible red and the infra-red regions (about 600 to 1,400 mμ), the sun being the best radiator.

Various artificial radiators are arc lamps with carbons having various kinds of cores, gas-filled tungsten lamps, quartz-mercury arc lamps, carbon-filament lamps, and open radiant heaters. They are used for thermal nerve stimulation in the treatment of disease, the penetration of the rays to from 10 to 30 mm being termed deep therapy.

After numerous experiments, Hill found that 60 per cent of the persons examined experienced difficulty in breathing through the nose when exposed to certain infra-red rays given off by dark or dull-red sources, showing that these rays affect the sensory nerves of the skin which produce the reflex effect of closing the nostrils. He believes this to be the chief reason for the feeling of stuffiness experienced in an overheated room, and terms these rays "nose-shutters." The effect can be neutralized by fanning the face or by the action of certain other rays, which he terms "nose-openers," the latter being obtained from luminous sources of heat. They also are neutralized by water vapor.

The skin now is regarded as an important organ of the human body.

There is a possibility that radio waves eventually may affect photographic plates and even produce sensations of heat. The higher frequencies of radio already may be said to be in the long-wave length portion of the infra-red region and photographic plates constantly are being made more sensitive to long-wave length radiation. Plates that are from a hundred to a thousand times faster than formerly now produce good photographs of objects in the radiation from flatirons in total darkness. The plates already have enabled astronomers to discover iron spectral lines in certain stars. It also appears certain that eventually radio waves will affect photoelectric cells.

While flying over the city of Washington engulfed in fog and smoke so dense as to make the city invisible, an aviator obtained a good photograph of the city on a film sensitive to infra-red rays.

A reflector with a sensitive thermocouple within it is moved about until the maximum reading is obtained on a meter, when it is known that it is pointing at the sun, although clouds and fog may be so dense as to prevent its direction being found by other methods. Infra-red rays penetrate clouds and fog and affect the thermocouple, the instrument being so sensitive that it is said to be capable of recording the heat rays from a man's face a mile away. Although the aviator could not see it because of the haze, Mount Shasta was photographed from a distance of more than 300 miles.

It is obvious that when these invisible rays are exploited on a large scale, a new art will be developed, navigation by sea and air in cloudy or foggy weather becoming safe and sure. Thus the presence of icebergs and other objects or radiators which may or may not emit signals, may be detected as objects to be avoided or as guides to a safe course.

170. The Visible Spectrum.—This subject was dealt with in Chap. XV. The visible spectrum extends from about 700 mμ in the red to about 400 mμ in the violet. The only reason for the name of this spectrum is that human eyes, which were evolved in the entire spectrum, convey to consciousness only the effects of radiation within this range, the middle of which approximately corresponds to the maximum of radiation reaching the earth from the sun.

Plants, for example, thrive best in full sunlight. Experiments show that if two identical plants are exposed to different wave lengths of light, there is a great difference in their rates of growth. Thus, if one plant is exposed to blue-green light and another is exposed to yellow-red light, the rate of growth of the latter is several times that of the former.

171. The Ultra-violet Regions.—In 1801, Ritter discovered that silver chloride became blackened when placed beyond the violet region in the visible spectrum. The ultra-violet region extends from the end of the visible violet (about 400 mμ) to the Röntgen (x-ray) region.

The invisible short-wave length ultra-violet radiation produces sunburn and tan on human skin, brings about chemical changes, destroys germs, affects photographic plates and films, produces fluorescence, and is of benefit in rickets and tuberculosis, at least to the same extent as sunlight, when properly administered. Hertz discovered that violet and ultra-violet light more readily

caused an electric spark to start. He also discovered that ultra-violet light causes the discharge of negatively charged bodies, as previously stated.

Ultra-violet radiation reaching the earth is sharply cut off at about 195 mμ due to absorption in the earth's atmosphere and, probably, to the presence of ozone in the upper atmosphere, since ozone is produced by ultra-violet radiation. Since human beings are not accustomed to ultra-violet radiation of shorter wave length, and since such shorter wave lengths (about 180 mμ) readily are artificially produced, physicians are inclined to be cautious about recommending human exposure to the shorter waves from arc lamps and the like until more definite knowledge is gained regarding their effects.

Short-wave (200 to 300 mμ) ultra-violet radiation is employed in sterilization, as of water, the effect depending upon the intensity and duration of radiation, and it is believed that radiation with a wave length shorter than 280 mμ destroys tissue, the beneficial radiation employed in the prevention and cure of rickets thought to be located between the latter wave length and 320 mμ. It also appears to be an important factor in the cure of skin diseases, extrapulmonary tuberculosis, chronic anemias, and other diseases, but there is still much to be learned regarding the actual effects.

Tanning of the human skin is a protection to excessive radiation, but permits the vitalizing radiation to pass through. Shull and Lemon discovered that the supposedly harmful shorter rays cannot penetrate the outer coats of seeds of various kinds and sizes, while those of longer wave length, which have a stimulating effect, pass through. Thus it appears that nature has provided protection in the evolutionary process and that filters should be used in connection with arc lamps and the like to eliminate harmful radiation which cannot reach the earth from the sun, for the reasons above mentioned, when taking ultra-violet "sun baths."

Wakeman and his associates found that pure nicotine lost half its poisonous effect under ultra-violet radiation from an arc lamp unless overexposed. Bowden and Snow discovered that vitamin A, which prevents infections and promotes growth, was converted from the yellow pigment carotin found in egg yolk, butter, carrots, and so forth, upon their exposure to 265 mμ of ultra-violet radiation.

It has been fairly well proved that ultra-violet radiation is a producer of vitamin D directly in the human being and that vitamin D and radiation of certain wave length produce bone growth and calcification. Sperti and his assistants discovered a process whereby vitamin D may be added to many articles of food and medicinal products and for sterilization in the prevention of food spoilage, thereby rendering immune various germs of fermentation, yeast molds, and the like. They also believed that disease germs possibly may be destroyed inside the human body without injury to living tissue. If a lower frequency was used, however, the vitamin D was destroyed. It thus appears that such effects are of a resonant nature. The discovery that food substances, such as oils and powdered milk, which have been exposed to ultra-violet radiation produce beneficial results in such conditions as rickets, led to the extensive application of the principle. The rickets-preventing vitamin D is formed by the action of ultra-violet light on ergosterol.

Vitamin B, recently isolated by Windaus, is found naturally in vegetables, cereals, eggs, milk, liver, and pancreas. More recently, Guha and Chakravorty discovered that vitamin B also is produced by ultra-violet radiation, as reported in *Nature*.

According to Coblentz, the penetration of rays from arcs into human tissue varies from about 0.1 mm in the far ultra-violet to about 0.5 mm in the near ultra-violet; from 1 to 30 mm in the visible and near infra-red (560 to 1,500 mμ) down to about 0.1 mm again in the far infra-red (1,500 to 15,000 mμ).

172. Effect of Ultra-violet Radiation upon the Eye.—In an article in the March 26, 1932, number of *Electrical World*, M. Luckiesh called attention to the seriousness of this radiation upon the eye under the above title. This has been studied for the past twenty-five years, resulting in the findings that "(1) the reciprocity law (intensity $\times$ time = a constant) applies to physiological effects upon the eye for an intensity range of at least 150 to 1," and "(2) physiological effects are approximately additive for intermittent exposures, if the period of intermittency is less than 24 hours. For periods greater than 24 hours the effects partially disappear between exposures."

Within several hours after exposure there is a sensation of foreign-body irritation, the symptoms disappearing within a few days, except in cases of severe overexposures in which the cornea may become clouded. Snow blindness apparently may

result from overexposure to ultra-violet radiation on the eyes. Burge showed that when the radiation of the mercury arc was focused on egg-white and the material was later immersed in calcium chloride, coagulation was caused by wave lengths of 280 mμ and shorter wave lengths.

It is apparent that suitable protection to the eyes always should be worn when under exposure to these short rays. Such glasses are supplied by makers of ultra-violet light sources.

173. Sources of Ultra-violet Light.—Powerful sources of ultra-violet radiation are the electric arcs and sparks, notably the quartz-tube mercury arc operating at a pressure slightly above that of the atmosphere, sunlight lamps, carbon arcs and iron arcs.

174. Transmission, Reflection, and Measurement of Ultra-violet Radiation.—Although varying with the composition, the approximate short-wave limit of transmission of ordinary glass is at about 320 mμ. While it is not difficult to make a glass transparent to ultra-violet radiation, such glasses decrease in transparency when exposed to solar or certain ultra-violet radiation for some time. On the other hand, the practical limit for fused quartz is about 185 mμ, and for natural quartz crystals and fluorite it is about 125 mμ.

Chromium and aluminum reflect about half the incident ultra-violet radiation, while tin reflects very little. Pigments reflect in varying degrees and bleached cotton reflects the most among the common fabrics.

The measurement of ultra-violet radiation has not yet been perfected, but important advances are being made in a number of laboratories. The reddening of the skin has been used as a measure in the past, much as the color of light to the eye has been employed. Chemical or biological effects, such as blackening of sulphides, bleaching of dyes, effect on photographic paper, and so forth, are in general use. In Victoreen's method a definite electric potential is induced between two electrodes, which potential gradually is neutralized by the electron emission from the cathode due to the ultra-violet radiation, the rate of neutralization being a measure of the intensity of the radiation, but the measurement of the wave length is not so simple.

175. Commercial Uses of Ultra-violet Light.—Check paper treated with a white fluorescent powder, called aesculin, makes it possible for the bank teller to detect erasures and changes,

not normally evident, by exposing the check to ultra-violet radiation when the spot where the erasure has been made does not glow like the rest of the check. Similarly, invisible inks which glow under ultra-violet radiation can be used for various purposes of identification.

Art critics thrive on their knowledge of the pigments used and the definite ways in which they were mixed by the great artists. By photographing a painting successively with several different colors of monochromatic light, including infra-red and ultra-violet, the photographs have different appearances depending upon the exact pigment used and how they reflect in different ways. There also are other methods. Thus copies and forgeries now may be detected.

It has been found that mixtures of dilutions of vegetable oils can be detected by an experienced observer through the fact that the mixture is fluorescent while the pure oil is but slightly so.

Most of the smoke of cities is produced by furnaces in small apartment houses, small office buildings and private houses. Large factories and power houses cannot afford to waste fuel through producing smoke. Because this smoke shuts out ultra-violet radiation it is considered more harmful from this viewpoint than from its inhalation. Instruments now record the transmission of ultra-violet radiation through smoke and, by comparison with another recorder outside the smoky area, show how much ultra-violet radiation is lost through a smoky atmosphere.

An interesting effect produced on egg production has been reported. A flock of pullets was divided into two groups of 180 each housed in a two-section henhouse, insulated but unheated, each group receiving the same food and ventilation. Egg production was checked from November 1 to January 1 and was found to be the same for each flock. Beginning January 1, group A was treated with ultra-violet radiation by means of two standard sunlamps suspended four feet above the feeder, being automatically turned on at 5.30 A.M. and off at 7.30 A.M. Sufficient illumination was provided group B so that each flock would be off the roosts at the same time.

After a month's test, the untreated group had gained 13 per cent over normal production and the treated flock had gained 92 per cent. Group A showed an egg production of 2,150, while group B showed 1,263 eggs for the month.

It is reported that the Gaument laboratories in France have successfully demonstrated a new process of ultra-violet sound-on-film recording. The full width of the film is used in place of the present sound track by this method. Reproduction is accomplished by means of a mercury-arc lamp. The sound record is recorded on one film and the picture on another, similar to present studio methods using two films. Later the two are superimposed to make the finished product. The sound record is made by the use of ultra-violet rays and is not sensitive to the ordinary projection light so that no images from the sound appear on the screen.

Reflected infra-red and ultra-violet rays have been employed in burglar alarms, as mentioned in Art. 156.

CHAPTER XXII

X-RAYS

From the artificially produced radio waves, and on through the infra-red, visible, and ultra-violet wave-length ranges, we now come to another group of artificially produced waves by means of which we not only can examine the interiors of opaque bodies but also can study the very atoms.

176. Discovery and Production.—In 1895, the same year in which J. J. Thomson proved that cathode rays are deflected by electric charges, Röntgen surrounded a tube producing cathode rays with black cardboard and discovered that a screen coated with barium platinocyanide became fluorescent even at a distance of 2 m from the tube.

These rays cannot be deflected by a magnet as can cathode rays, although both excite fluorescence, penetrate materials, ionize gases, and discharge electroscopes. Röntgen called them x-rays because he did not know their nature, but now they are known technically, if not popularly, as Röntgen rays.

The anode or target of a modern x-ray tube (Fig. 216) is made of metal (usually tungsten), with its face set at such an angle to the cathode stream that the middle of the x-ray beam shall be emitted from one side of the tube. The cathode rays are focused from the cathode so as to strike the central portion of the target and produce x-rays at that place.

Radiographs are the shadows cast upon a photographic plate or film due to the absorption of some of the x-rays by interposed bodies. Fluorescent screens are used in direct observation and fluorescent intensifying screens also are sometimes placed back of photographic plates in radiography.

The discovery by Laue that a crystal, such as calcite, acts as a three-dimensional diffraction grating, proved that x-rays are identical in nature with light, heat, and radio waves, but of much shorter wave length. The range of x-ray wave lengths, as commonly employed in practice, lies between the extreme ultra-violet and gamma-ray (radium radiation) regions, that is, from about

0.2 (hard) to 0.5 mμ (soft), the "hardness" of an x-ray increasing as the wave length decreases.

In general, the x-rays of shorter wave length have the greater penetrative power, or penetration, the absorption being proportional to the ratio of wave length to the atomic weight of the object irradiated. Thus long waves, which readily will penetrate a given thickness of aluminum (atomic weight 26.96), may be absorbed by the same thickness of lead (atomic weight 207.2). For a given atomic weight, the absorption increases nearly as the cube of the wave length. That is why aluminum is used as a window through which x-rays can pass in a wholly enclosed oil-immersed unit, while lead is employed to prevent x-rays from reaching places where they are not wanted, as to protect operators and the portions of patients which are not being treated.

177. Dangers.—One of the most important effects of x-rays is their destructive effect upon tissue, and this cannot be too greatly stressed. These so-called x-ray burns may develop from a single exposure, in which case they are termed "acute," although they may not be noticeable for several days after exposure, or they may be cumulative as the result of small exposures which an operator might receive in his daily work if unprotected, in which case the burns are termed chronic. The presence of x-rays in the vicinity of high-voltage electron tubes may be detected by placing photographic plates or films in their holders near the tubes.

In therapy or medical science, the soft (long-wave length) x-rays are filtered out, so that they cannot burn the patient's skin, by passing the x-rays through thin sheets of copper (atomic weight 63.57) up to about 1.5 mm thick, or up to about 5 m for aluminum (atomic weight 26.96) with the voltages commonly used. Operators are protected by lead sheets which should be at least 1 mm thick for voltages up to 75 kv, and 5 mm for 225 kv, and by lead-glass windows. Lead or barium oxides in aprons and gloves provide further protection. Lead placed about the tube stops the x-rays near the source. Sometimes the entire room is enclosed in lead, as when very high voltages are employed. Protection from electrical shocks to patient and operator also is provided.

178. The x-ray spectrum consists of a continuous background, whose wave-length range depends upon the voltage used, upon which there are superposed (above certain critical voltages) more

intense spectral lines, obtained by diffraction with a crystal, whose characteristic wave lengths depend upon the element, or elements, comprising the target. From these spectral wave lengths is determined the quality of an x-ray beam.

179. Secondary Radiation.—Much as secondary electrons are driven from metals when struck by electrons, so also is secondary radiation of x-rays produced (above certain minimum voltages) by the irradiation of a body with x-rays from the primary source, the secondary radiation being composed of scattered radiation of approximately the same wave lengths as the rays from the source, the characteristic radiation of the object upon which the primary rays fall, and electrons (called corpuscular radiation). Scattering, therefore, also occurs where the beam passes through the glass wall of the tube.

The Compton effect is the name for the phenomenon of scattered x-rays having longer wave lengths than the original rays, as when the latter pass through gases or other matter, the alteration of the wave length being assumed to be due to the exchanges of momentum and energy between the x-rays and the electrons in the atoms.

In all forms of radiography, much of the secondary radiation scattered from the object or objects under examination is eliminated by the use of the Potter-Bucky diaphragm, thus clarifying the photograph.

180. Intensity and Penetration.—The quality of an x-ray beam is measured by its intensity and penetration, the former, which depends upon the shortness of its wave length, being the more important.

After the dangerous effects of absorbed x-rays were discovered, the proper dosage that would sufficiently affect the body in therapy, as in the treatment of diseases of a cancerous nature, and skin and other diseases, without harming the patient were determined and techniques were developed through experience. Burning a patient may not be so bad as undertreating him, especially in such cases as cancer.

Within reasonable limits, the biological effect within the tissue is proportional to the ionization produced by the same kind of x-ray beam in dry air. The amount of this ionization may be measured by a milliammeter connected in series in a circuit containing an ionizing chamber or cylinder. Hence the intensity and the biological effect, as determined through experience, can

be measured in terms of milliamperes. Such a dosage meter was developed by Taylor for the U. S. Bureau of Standards. There are now a number of dosage meters available, calibrated in terms of the ionization of a cubic centimeter of air, the unit being the röntgen or x-unit, equal to 1-thousandth of an Ångström unit. Formerly the dosage was measured by the product of the applied voltage and the tube or space current in milliamperes.

The penetration may be measured by placing various thicknesses of lead above the photographic plate or film exposed to the rays.

181. X-ray Tubes.—Modern x-ray tubes are of the Coolidge or tungsten-filament type (Fig. 216) wherein the tube or space current strength generally is regulated by the filament temperature. Tubes are of the air-cooled, water-cooled, and oil-immersed types, the water-cooled tubes having cooling water supplied to the

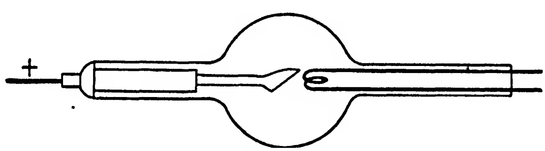


FIG. 216.—Principle of Coolidge x-ray tube.

anode or target. If the anode is not grounded, the entire water-cooling system must be insulated from the ground.

These tubes and their modifications range in size from the remarkably small portable types to the huge cascade or multi-sectional tubes operating at millions of volts, the voltages being generated in a number of ways, usually by transformer and rectified by means of synchronous switching devices (which are very noisy) in the tube circuit or by means of large rectifying tubes (kenetrons) which insure quiet operation. It has been shown that the x-ray output per milliampere is the same from a kenetron machine as from a properly adjusted mechanical rectifier. The fundamental principle of the mechanical rectifier is shown in Fig. 217 and that of the kenetron in Fig. 218. By the simple introduction of a mercury-arc or other rectifier in series with the primary of the x-ray transformer (Fig. 219), Kearsley has increased by several fold the allowable output from a given half-wave outfit.

Besides the volt-ampere input and operating time of the tube, the size of the focal spot determines the power limitation. The

space current is measured by a milliammeter in the tube circuit (Fig. 217) and the voltage may be measured by a sphere gap connected across the tube terminals or by a voltmeter consisting of a milliammeter in series with a shielded resistance of about 100 megohms (Fig. 217).

Voltages and current strengths employed in medical diagnosis range from about 40 to 100 kv and from 10 to 100 ma., respectively, while exposures vary from a hundredth of a second or less

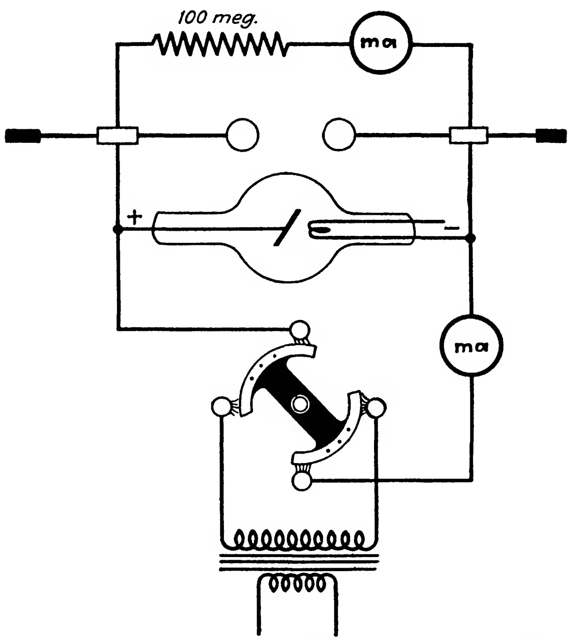


FIG. 217.—Principle of the mechanical rectifier driven by a synchronous motor. Two methods of measuring the voltage are shown.

to half an hour or more. Voltages up to 100 kv generally are used for superficial treatment and up to 220 kv for deep therapy.

182. Giant X-ray Tubes.—The experience gained with high-voltage cathode-ray tubes, wherein the cascade or multisectional system is employed, led Coolidge to apply this principle to the x-ray tube, each section being capable of continuous operation at 300 kv. The general scheme is illustrated in Fig. 220. Such a three-section tube, referred to in Art. 163, operates at 900 kv. In the second installment of a series of articles on the development of modern x-ray generating apparatus in the December, 1930.

number of the *General Electric Review,* Coolidge has briefly described this generator, the transformer of which is of the open-core type and called an induction coil.

Since the top of the secondary coil is at the highest potential, a flared-out split aluminum spinning electrically shields the upper end of the core and serves as a connection to the cathode of the tube. Arc-over from the aluminum spinning to the upper end of the core is prevented by the spherical shield shown thereon, which consists of a wooden sphere overlaid with narrow strips of sheet aluminum connected to the core.

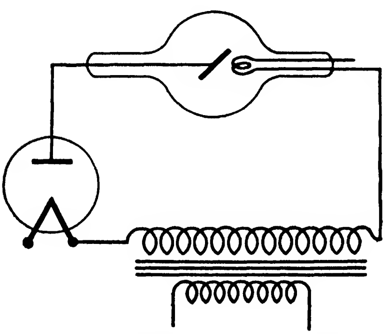


Fig. 218.—Principle of the kenetron x-ray machine.

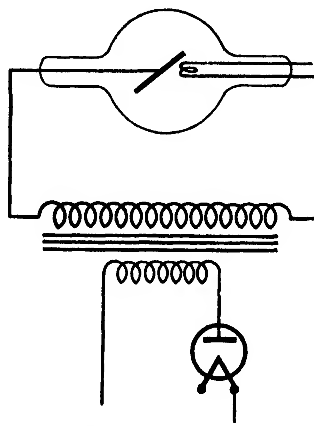


Fig. 219.—Principle of Kearsley's x-ray generator.

The target is placed inside of the copper shield and near the outer end of the anode arm at the left in Fig. 220, the x-rays issuing sidewise through a hole therein.

The California Institute of Technology also has an x-ray tube 30 ft. high which is regularly operated at 1,200 kv. Careful measurements of the intensity of radiation produced and the limit of the short-wave radiation were made by Lauritsen, the intensity being 20 röntgens at a distance of 70 cm from the target. It has been estimated that in quality of radiation produced, this tube equals many times the amount of radium now available in the world for medical use, and equivalent to about one hundred million dollar's worth of radium. The tube is operated with alternating current. Another giant tube, built by Tuve, operates at 2,000 kv—2 million volts.

In 1932, K. T. Compton announced that a 15,000-kv x-ray tube, fifteen times as powerful as the 900-kv tube referred to and almost eight times larger than the 2,000-kv tube, would be constructed for operation by the Van de Graaff electrostatic generator (Art. 18).

183. Special Tubes and Devices.—In a stereoscopic x-ray instrument perfected at the California Institute of Technology by DuMond, Hoyt, and Brandmyer, two tubes, set the same distance apart as human eyes and operating on 50-c current, alternately and periodically cast shadows on the screen at

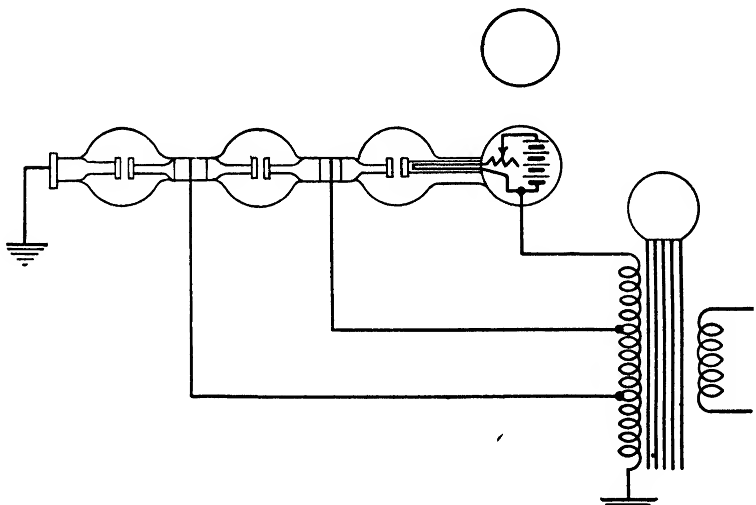


FIG. 220.—Principle of multisectional x-ray tube.

slightly different places, the beams crossing each other in the patient's body before reaching the screen, thus producing a transparent shadow of the same size, shape, and depth as the person. By means of a synchronous rotating shutter before the eyes, each eye sees only one shadow, thus giving the impression of a three-dimensional stereoscopic plastic relief, the image appearing in space before the screen as an exact scale reproduction, by means of which a physician can see broken bones, for example, as clearly as if they lay before him, and internal measurements may be made with calipers.

A Westinghouse super-speed tube developed by Morrison and Ulrey has a third electrode or grid which, when "tripped," releases the charge of a condenser in a manner similar to that

described in Art. 164, thus making it possible to take x-ray snapshots in less than a thousandth of a second; these are not blurred or hidden by the motion of the patient's muscles. It may be operated from an ordinary house-lighting circuit.

By means of a tiny camera and lighting bulb that may be easily passed into the stomach, as described by Thal, the physician can see the camera in the stomach by means of x-rays and guide it to the best place for the more exact location of ulcers and other lesions of the stomach.

Fricke and Sizer have produced radiographs of the internal structure of insects by means of a specially constructed x-ray tube and dental films.

184. Specimens of Technique.—Preparations of barium taken internally aid in the diagnosis by causing sharper shadows to be cast by the x-rays. Iodized oil introduced into the bronchial tree causes practically no irritation, yet it causes shadows which outline exactly that portion of the bronchial tree which is to be irradiated. A small amount of thorium dioxide solution injected into the veins causes the shape of both spleen and liver to be clearly seen. Teething infants chewing paint from toys and woodwork are subject to lead poisoning. The lead can be seen stored in the bones as a dense band at the growing margin. By the use of a strontium technique, Menees demonstrated that the sex of a child may be determined three months before birth. Engineering has done much to aid the physician, as in the early diagnosis of tuberculosis, wherein very rapid exposures are timed to conform to a particular phase of the cardiac cycle.

185. Some Biological Effects.—Two truisms appear to be that cancer is the most important medical problem, and that success in the battle against it depends upon early diagnosis. According to Isaacs, who made observations of 923 patients before announcing his findings, the life of the cancer cells is speeded up by the exposure to x-rays, so that they become old and die much sooner than normally, whereas other cells, like those of muscle, nerve, and fibrous-tissue cells, live long after they become adults and do not die of senility for a long time after being stimulated by x-rays, while some cells, like germ cells and white blood cells, die fairly quickly after treatment.

Radiologists have noted that there is a lag between the time of x-ray treatment and the effect that is produced. According to Roffo, a chemical compound called cholesterol, found in all

animal fats, in oil, and in many organs of the body, prepares the soil for cancer growth, cancerous tissues showing an increased cholesterol content compared with normal tissues, especially as regards the skin wherein a fixation of cholesterol in the tissues is favored by exposure to light.

At the Memorial Hospital, New York, under the direction of Dr. Failla, cancer patients suffering from tumors widely disseminated throughout the body were placed in four beds simultaneously. They received treatment from a single tube continuously for periods of one or two weeks, it being necessary to start with a very low dose while the reactions were being studied.

At the same hospital, a new building was erected for the housing of the Coolidge 900-kv tube referred to in Art. 182, where the staff obtained information sufficient to begin the treatment of patients, using 700-kv and 5 ma. for continuous operation during several hours, the radiation being equivalent to that of 450 g of radium, costing 22 million dollars. These x-rays could be measured after passing through a lead plate 1½ in. thick. A part of the tube was surrounded with a lead sleeve more than 3 in. thick, and a lead room, from 1 to 2 in. thick all around, was constructed to confine the rays thereto. It was found that, from a practical standpoint, the x-rays from the 700-kv tube, ordinary 200-kv tubes, and gamma rays from radium do not have the same effect on human skin and tissue.

Shull exposed corn, wheat, oats, and sunflowers to x-rays for various periods up to 10 min., the effect being to speed up their life processes, except in cases where the exposure was too long, as for 10 min., the latter group being badly burned while the 3-min. treatment was most beneficial to sunflowers. Wild corn plants appear to have been changed from annuals to perennials at Cornell University by treating the seeds with x-rays.

According to Timoféeff-Ressovsky, x-rays do not only speed up evolution but also can reverse its direction. While offspring from fruit flies, whose reproductive cells had been exposed to x-rays, had marked changes in color, shape, and size of eyes, bristles, and so forth, when these in turn were exposed to the rays, they produced normal offspring. According to Snell, although x-rays long have been known to cause sterility in male animals if applied in sufficiently heavy doses, sterility in mice does not occur until two weeks after exposure.

Obreshkove and King have succeeded in producing a hunchback on a water flea by x-rays.

186. Industrial Uses.—X-rays easily show a lead bullet in a rifle barrel because the atomic weight of lead is 207.2 while that of iron is 55.84. In other cases the difference in atomic weight is not so marked, but x-rays will show whether or not a metal is of homogeneous structure or whether any flaws are hidden therein that might endanger life or property. Cement, steel castings, or even lead, are subject to x-ray examination.

The voltages used in industrial work usually are over 100 kv, the time of exposure being computed by taking the continued product of the voltage, the current strength and the time. Charts are provided for making proper estimates for the various materials and their thicknesses. The air-cooled type has been used to considerable advantage in industry, since the high voltage gives the necessary penetration required for the examination of the heavier metal objects.

Thus steel castings, welds, and so forth, are examined by x-rays, the training of welders for the development of a perfected technique and inspection to assure freedom from defects being an important item. Photographs can be taken through a 4-in. iron plate with the Coolidge 900-kv tube.

According to Hiller, using 30 kv and 10 ma. at 30-in. focal distance, the time of exposure varies from about 10 sec. for 2½-in. to 50 min. for 4½-in. steel.

An important application of x-rays to industry is the inspection of parts ready for assembly. An example is a twisted wire hidden within the cathode of a heater-type vacuum tube which, if out of alignment, may cause the failure of the assembled tube. These and other parts are x-rayed by the trayful and all showing defects promptly are rejected.

187. Identification by X-ray.—Poole discovered that of over 2,000 radiographs of the nasal sinuses of humans taken over a period of years no two were exactly alike. He has suggested that this method of identification should prove useful to police departments and life insurance companies. Radiographs of teeth occasionally have been used for identification purposes.

A special ink that absorbs x-rays has been developed for marking x-ray films for later identification, as in medicolegal proceedings.

188. Other Methods of Producing X-rays.—In 1931, Reboul produced x-ray photographs without the use of tubes, by driving electric currents through high-resistance solids as, for instance, magnesia, alum, and yellow oxide of mercury. This tends to show that there are less free electrons in a given volume of high-resistance material than in a similar volume of metal, for example. It is known that high-speed electrons are required for producing useful x-rays and, since the current strengths are relatively small in high-resistance materials, the resistance is proportional to the average electronic velocity for a given current strength.

Locker has reported a new process of x-ray generation caused by the passage of a swiftly moving electrified particle through gas. He discovered a new process of ionization while investigating the nature of cosmic rays.

Coates and Lawrence, using 1-million-volt mercury positive ions, recently succeeded in producing so-called positive x-rays which, however, are comparable only to 10,000-v negative (ordinary) x-rays produced by the impacts of negative electrons.

CHAPTER XXIII

MATTER AND ENERGY

Thoughts become things when man visualizes various *shapes* of matter and then makes his dreams come true, as in beautiful works of art, architectural structures and useful machines. But when the shapes are destroyed, as by heat, even the metals of the most intricate machinery become mere chance-shaped masses. Our remote ancestors must have marveled to see pieces of wood, for example, lose their shapes, and vanish to the accompaniment of flame, smoke, and crackling sounds, leaving behind only a small amount of residue.

Fire descended from the heavens, hurled by the gods in thunderbolts, and, setting the forests afire, endangered the lives of man and beast. But Prometheus founded civilization by bringing stolen celestial fire to man, who then learned how to use it to good advantage, and later how to produce it with flint and steel, and also by friction.

The alchemists of the Middle Ages sought the transmutation of the baser metals into gold and, among other things, also sought the elixir of life. Democritus expounded the theory that matter is made up of ultimate particles which he called atoms. Now man not only has learned that certain kinds of atoms are naturally flying apart, but he also has learned how to smash atoms that do not naturally disintegrate and to form new atoms through synthesis, actually accomplishing transmutation, though not yet on a practicable scale.

189. Chemical Theory.—From the alchemy or immature chemistry of the Middle Ages the science of chemistry gradually emerged. Before the atomic theory was formulated, Richter proposed numerical relations between the equivalents obtained by him for the various bases and acids. In 1803, Dalton made the first attempt to compile a table of atomic weights. He gave that of hydrogen as 1, oxygen 5.5, and sulphur 14.4, and included a number of compounds. The table which he presented five

years later contained the atomic weights of thirty-seven substances. Thomson and Wollaston, and Berzélius, also published further tables of atomic weights.

In 1815, an anonymous article (written by Prout) was published, wherein it was stated: "I have often observed the near approach to round numbers of many of the weights of the atoms before I was led to investigate the subject." He also wrote a second paper. His views attracted much attention, particularly as they referred to hydrogen being the primal element and the atomic weights of the other known elements being multiples thereof, and there was much disagreement about the correctness of the theory.

In 1869, Mendeléeff announced his famous Periodic Law of the chemical elements, and there was much discussion between Mendeleef and Meyer as to the relative merits of their claims to its authorship. Mendeleef's second table, published in 1871, was more complete. This law states that "The properties of the chemical elements are periodic functions of their atomic weights."

Thus, after a given cycle of consecutive elements in the atomic-weight scale is completed, another cycle begins, each cycle belonging to a family or group consisting of the elements in the same step or position in the other cycles. This is best understood by laying out a diagram or graph with specific heats, atomic volumes, melting points, and so on, plotted *versus* atomic weights. Each curve rises and falls again as the next cycle is approached, thus resembling complex waves. The existence and properties of a number of elements have been predicted by the aid of this law before their discovery. Family resemblances now are considered instead of ascending atomic weights.

All during this time Prout's hypothesis would not down. Mallet revived it in 1880, and it was discussed by Crookes, Meyer, and others. In fact, it is very much to the fore just now, though in a much advanced form.

190. Nature the Alchemist.—For a great many years there was a gap in the list of atomic weights, for the elements corresponding to those missing had not been discovered. According to the classification of Mendeleef and Meyer there should be 92.

In 1896, Becquerel discovered that the salts of uranium and the metal itself affected a photographic plate wrapped in aluminum foil or in black paper, and that the rays ionized air to make it conducting. This phenomenon was termed *radioactivity*. A

few months after Becquerel's discovery, Mme. Curie began an investigation of all the known elements to find others that possessed the property of radioactivity. She found that the uranium ore pitchblende, largely uranium oxide, would discharge her electroscope (Art. 20) about four times more rapidly than would pure uranium. With great patience she separated a few hundredths of a gram of a metal, allied to barium in its chemical properties, which she named *radium*, from several tons of pitchblende.

Uranium naturally degenerates or is transmuted into radium, but the radioactivity of the latter is about a million times greater than that of uranium. Rutherford and Soddy have shown that there is a continual disintegration of the radioactive elements and that they naturally are transmuted from one into another. Uranium and thorium branch along three distinct paths and end up as lead, though in three isotropic (same physical properties) forms. While some radioactive substances are transmuted in a very small fraction of a second, other transmutations require millions of years. Thus while uranium I has a half-life of 6.5 billion years, radium C′ has a half-life of only 13 billionths of a second. The shorter the life of an atom, the greater is the velocity of the particle ejected from it.

Rutherford showed that radium emits three kinds of radiation, the alpha, beta, and gamma "rays," which can be separated by passing them through a strong magnetic field, only the alpha and beta rays being deflected thereby in such opposite directions as to show that the alpha rays, which have small penetrating power, are positive ions of the same general nature of canal or positive rays (Art. 54) but having the same mass as the helium atom of atomic weight 4 and having a double positive charge, while the beta rays are highly penetrative electrons, otherwise identical with cathode rays. The alpha and beta rays also can be deflected in an electric field. The velocities with which these particles are emitted are different for the various radioactive atoms, the highest velocities for the alpha particles being about 12,000 mi. per sec., while the fastest of the beta particles or electrons have speeds closely approaching that of light.

By observing the mass of these fast electrons the prediction that the mass of an electrical particle should increase with its speed has been confirmed. The electrons ejected from the nucleus of the atom are termed primary beta rays, while those

set free from the outer shell of the atom are called secondary beta rays. There is no essential difference between these electrons and the electrons set free from an incandescent metal, from a photoelectric surface, or from those in a cathode-ray tube.

The gamma rays are of exceedingly high penetrating power; they have properties identical with x-rays, and always travel at the velocity of light. They cannot be deflected in either a magnetic or an electric field. Like x-rays, they are characteristic of the kind of atom from which they are emitted. They are due to the emission of beta rays from the atomic nucleus. Just as electrons of lower velocity produce x-rays, so also do higher-speed electrons produce the shorter gamma rays.

191. Characteristics of the Rays.—Alpha, beta, and gamma rays all affect photographic plates and films, ionize gases, cause phosphorescence in certain substances, and produce chemical effects, the glass container of a radium preparation eventually having a deep violet color.

The wave-length range of the gamma rays lies between the x-ray and cosmic-ray regions, extending from about 1.365 (soft) to about 0.0047 (hard) Å. The shorter the wave length, the harder or more penetrating is the ray and the smaller is the absorption coefficient.

192. Counting the Particles.—A convenient means of counting the alpha particles is to note through a low-power microscope the scintillations or tiny flashes where they strike crystalline zinc sulphide. The alpha and beta particles also may be counted in the aggregate, by noting the change in the strength of a current in an ionizing chamber, or by the heat effect.

The so-called Geiger counter, originally designed by Rutherford and Geiger for counting alpha particles, consists of a metal cylinder with a wire running through the center and insulated therefrom, the whole being enclosed in a glass tube filled with gas. A difference of potential of about 1.5 kv is applied between the metal cylinder and the wire to keep the gas just on the point of breaking down, the cylinder being of negative polarity and the wire being connected to an electrometer or to the grid of a vacuum tube.

The entrance of a single alpha particle through the window at the end of the tube near the end of the wire causes it to be indicated, recorded, or counted. The counter is so sensitive that a single electron causes the associated apparatus to function.

This is the device whereby an electron was "dropped" and the "impact" broadcast to the radio audience.

193. The Wilson Cloud-expansion Chamber.—This is used for studying the tracks of rapidly moving particles. Moisture in the air condenses around suspended dust particles and then falls in drops as rain. Wilson found that the tracks of moving electrons could be made visible by shooting them through water vapor on the point of condensing under expansion.

By means of an electrically charged plate the droplets could be held in suspension. Although this method was employed in determining the approximate charge of the electron, Millikan employed single oil droplets charged with various numbers of electrons. By observing its fall under the action of gravity and its rise under the influence of electric charges on plates between which each drop was suspended, he measured the charge of the electron with greater accuracy than had been accomplished by previous methods.

194. Gamma Rays and Radium.—The alpha rays are easily stopped by a few sheets of paper, or about 8.5 cm of air, the beta and the weak gamma rays by about 3 mm of lead. The more penetrating gamma radiation, however, keeps on coming even through as much as 4 in. of lead. An air space 116 ft. thick would be needed to reduce their strength to the same degree, falling off as the square of the distance.

The physiological effects of the rays from radioactive materials are similar to those of x-rays, causing severe burns unless precautions are taken. Radium burns form on normal tissue exposed too long to the action of the rays, but they may not appear until two weeks or more after exposure. If they are severe they may turn to cancer. On the other hand, the therapeutic value of radium in healing certain cancerous growths appears to be well established.

It is now well known that x-rays speed up evolutionary change, and the effects of radiations from radium and other radioactive substances also have been investigated. It appears that in regions of high natural radioactivity in the earth there have been some small positive results. The great deposits of the radium ore pitchblende in the Great Bear Lake region of Canada discovered within the last few years undoubtedly will be the subject of investigation in this connection.

Gamma rays also have been used in examining welded-steel joints and steel objects. According to Doan, it is a slow and costly process to examine a steel object more than 3 in. thick by means of x-rays. With gamma rays, however, thicker castings can be tested and examined more rapidly and with much less trouble. All that is required is a capsule of radium salt the size of a pea, and ordinary photographic paper. The time of exposure depends upon the thickness of the casting, a few minutes being sufficient in most cases. It should be pointed out, however, that great precaution must be observed in handling and applying the radium salt, for anything that will act so quickly through so much metal may do much damage to tissue unless guarded against.

Radium (atomic weight 226), commonly employed in the form of one of its salts, has been used successfully in the treatment of cancer, for two reasons: (1) it may cause destruction of the malignant tissue, and (2) at the same time toughen the surrounding normal tissue. A thick, impenetrable coating is thus formed around the cancer, preventing the migration of the death-bearing cells to other parts of the body.

A gas, radon or radium emanation, is also produced in the radium disintegration and can be collected in suitable containers. It produces penetrating gamma rays for use in treating tumors.

When radium is placed in water, it decomposes it into its constituent gases, hydrogen and oxygen. There is only about half a pound of refined radium in the world.

One gram of radium develops 137 calories of heat per hour, due to the absorption of the particles ejected, about 88 per cent being due to the alpha particles. Radium has a half-life period of about 2,000 years, meaning that at the end of that period only one-half of a given amount will remain, and at the end of a similar period only one-half of that will remain, and so on forever.

It has been estimated that 1 g of radium contains about 5.5 billion foot-pounds of energy. One foot-pound is equal to 0.324 calorie; the power, therefore, is not very great and it can neither be speeded up nor retarded by any known means. Temperature has no effect upon it.

195. Inside the Atom.—One way to learn how a thing is made is to knock it apart, note what happens, and then figure out how the thing was put together in the first place. When atoms are bombarded with high-speed electrons, secondary electrons are

knocked out of them, but they are only valence electrons. It is exceedingly difficult to hit the nucleus or "heart" of an atom and knock out a *primary* electron therefrom, yet Rutherford did it in 1919 and since then others have been building bigger and better "guns" for their attacks on the hearts of the atoms.

Early in the present century, Mosely bombarded various elements with x-rays and obtained their characteristic x-ray spectra. He found that the characteristic x-ray wave lengths followed a scale, somewhat after the manner of a musical instrument, when hydrogen was given the atomic number 1 and uranium, the element of greatest atomic weight, was given the number 92, the order being that of decreasing wave lengths. Thus the atomic number of radium is 88. From the data thus obtained Mosely was able to show that all atoms are made up of but two "building blocks"—electrons and protons.

In what follows it should be remembered that the neutron and the positive electron have been discovered only recently and that new theories are being formulated. Nevertheless, we shall proceed pretty much in the usual manner in view of something more definite, but we shall give the views of scientists as we go along. Even as these words are typed new discoveries are being made and new theories are springing into being. This is but natural when the atomic nucleus is beginning to yield its secrets.

The proton is the hydrogen nucleus and it means "primitive substance." The atomic weight of an elementary substance is very nearly equal to the number of protons in the atomic nucleus, a portion of the mass of the proton apparently being converted into energy when protons combine, or are "packed," to form nuclei. The atomic number of an element is the excess of protons over electrons in the atomic nucleus, or the number of extra-nuclear electrons in the atom. Although there is one electron for each proton in an atom, half of the electrons are in the nucleus with the protons while the remaining half of the electrons are in the "shells." Into this general scheme the neutrons and the positive electrons somehow appear to fit.

The mass of the proton is 1845 times greater than that of the electron; the atomic weight, therefore, is almost entirely made up of the combined relative weights or masses of the protons. In what follows, the proton will have a relative mass 1. Thus the mass of the helium nucleus is 4. The proton is the

hydrogen (positive) ion—the hydrogen atom less one electron. The hydrogen atom consists of a nucleus of one proton with a single electron in motion about it to form the outer shell. The chemical nature of an element is determined by the distribution of the outer electrons.

The mass of the alpha particle is identical with that of the helium atom minus two electrons, as has been fully verified by experiment. After it has done its work, if it can capture two electrons it can become an ordinary helium atom. Thus an alpha particle may become a helium atom when two beta particles (electrons) are combined with it. Conversely, alpha particles may be formed artificially by removing two electrons from each helium atom.

The atomic number of the helium atom is 2 and its mass is 4. Since the positive charge of the nucleus is the same as the atomic number, its positive charge is 2 when free of its outer shell of 2 electrons. For any alpha-ray (or -particle) transformation, that is, when a helium nucleus leaves a radioactive atom, the new element thus formed has an atomic weight less by 4 and an atomic number less by 2 than its parent, while for any beta-ray (or -electron) transformation the new element has the same atomic weight or mass as its parent but an atomic number greater by 1, since the positive nuclear charge is increased that much by the absence of the ejected electron. These are called the transformation laws.

196. Isotopes.—Atoms of identical chemical natures and nearly equal atomic weights are called isotopes. The only means of separating isotopes are those that depend upon different masses of their atoms. They were discovered in radioactive substances in 1905.

While J. J. Thomson was studying the electric and magnetic deflections of neon-positive ions, in 1912, he found two positive ray parabolas, that is, the deflected rays did not fall on the photographic plate at the same place, but were slightly separated. By greatly refining the technique so that the different masses were more widely separated on the photographic plate, Aston showed that there are two kinds of neon atoms mixed together in the gas as to give the usual atomic weight of neon, that is 20.2. In copper, some of the atoms have the mass 63 and some have the mass 65, thus making the atomic weight or mass of copper 63.57, on the average, as found by chemical means. A

number of other isotopes of various kinds of atoms have been discovered.

Based on the numbers of electrons and protons in the known atomic nuclei, Urey predicted that a hydrogen isotope of atomic weight 2 would be found. Others also made similar predictions. By evaporating liquid hydrogen at very low temperature under a reduced pressure, the double weight hydrogen atoms were isolated, there being about one of this kind out of every 4,000 mixed hydrogen atoms. The outside coatings of the new hydrogen atoms are identical in all respects, including chemical properties, with ordinary hydrogen. Only the mass of the nucleus is different. The name "deuton" has been given this new kind of atom and its atomic number is 0. That is why there now are 93 known kinds of atoms instead of 92.

197. Total Energy Stored in Atoms.—The energy released from a gram of coal in the form of heat when it is burned is measured in tens of foot-pounds, whereas the energy released from a gram of matter due to its disintegration is measured in billions of foot-pounds. But during atomic disintegration, only helium nuclei, electrons, and gamma rays or waves are released. There are still the helium nuclei or alpha particles to be disintegrated into, perhaps, neutrons, and negative and positive electrons, with a further release of energy. When the neutrons have been disintegrated there will be another release of energy and there still will remain protons, and negative and positive electrons. When the protons have been disintegrated there will be a further release of energy and there still will remain at least the negative and positive electrons. There should be still more energy released, at least in the form of radiation, when the forms of the negative and positive electrons are changed to waves. Thus there is a vast store of energy in an exceedingly small amount of matter. The question has been asked: "Is matter crystallized energy?"

Man's methods of obtaining energy are extremely crude by comparison with the vast stores available, assuming that the store sometime can be efficiently used. But even with his crude methods, man has more than three available horsepower per worker and, since each man can produce about one-tenth horsepower, on the average, there is available about thirty times as much energy per worker as each worker could produce through his own muscular contraction.

CHAPTER XXIV

TRANSMUTATION AND COSMIC RAYS

Up to 1911, the solid atom of Democritus had been tacitly assumed, although it was known that negative electricity was concentrated in unit charges of very small bulk, while positive electricity was pictured as a jelly-like sphere of atomic size, with the negative charges imbedded in it. But Rutherford's scattering experiments showed that the large electrical forces exerted by the atom could only be accounted for on the basis of a highly concentrated positive charge and that the atom was substantially empty. Then arose theories of the atom wherein the hydrogen atom, the simplest of all, consists of one proton with a single electron describing orbits about it. The present picture is a nucleus consisting of protons (except in the hydrogen atom) with a series of nebulous negatively charged shells surrounding it, as outlined in previous pages. The latter may, however, be thought of as electrons describing orbits, only it is difficult to state where an electron may be found in an orbit. Now scientists are bombarding the atomic nuclei and actually are accomplishing transmutation in a small way. That this is taking place in the sun and elsewhere appears evident from the high-power cosmic rays which constantly bombard the earth's atmosphere.

198. Modern Alchemy.—Rutherford was the first to transmute artificially an element when he was said to have knocked H out of nitrogen, that is, he bombarded nitrogen with alpha particles and obtained hydrogen and helium. While the heavier elements are the ones which naturally disintegrate, the lighter ones are those which most readily are disintegrated artificially by the alpha particles (helium nuclei) shot out from the former. Although Rutherford succeeded in breaking down the nuclei of some other atoms in this manner, one of the products of disintegration being a high-speed proton, he did not break down oxygen.

In 1932, Bothe reported bombarding beryllium metal (atomic number 4, atomic weight 9.02) with alpha particles from radioactive polonium, obtaining carbon of atomic weight 13 and super-gamma or soft artificial cosmic radiation with more energy than that of the hitting alpha particles, which were estimated as one out of every 50,000. This process is not considered a disintegration of beryllium, since no protons were ejected therefrom, but a process of synthesis or building up, since a heavier element is formed.

Bothe and Becker found that lithium (number 3, weight 6.94), boron (5, 10.82), fluorine (9, 19), magnesium (12, 24.82), and aluminum (13, 26.96) also gave the soft artificial cosmic or hard gamma rays under the action of the polonium alpha particles, some of which also emitted proton rays, but beryllium gave by far the most intense secondary rays. In the case of beryllium, the addition of an alpha particle to the beryllium nucleus produced a carbon nucleus of atomic weight 13, the heavier nuclei being produced in synthesis or atom building by steps from the lighter.

Energy can be measured in terms of volt-electrons just as it can be measured in volt-coulombs. Whenever the statement is made that the energy is so many thousand or million volts, volt-electrons are meant.

Using only a few hundred thousand volts, Cockroft and Walton, in 1932, bombarded lithium (number 3, weight 6.94) with protons or hydrogen ions and obtained helium, with the additional release of 16 million volts energy. This is the first case to be reported where more energy was released than expended at each hit which, however, occurred only once in several million chances. The lithium atom is assumed to consist of one alpha particle or helium nucleus and three protons (hydrogen ions or nuclei) with the necessary number of electrons in the outer shell around them to make the atom electrically neutral. When a proton was added to the lithium atom by bombardment, the three protons already there apparently combined to form two helium nuclei, each of which consists of four protons and two electrons. Recently, Cockroft changed beryllium into lithium and helium, boron into three helium atoms, and fluorine into oxygen and helium, through hydrogen bombardments.

The work of Cockroft and Walton was confirmed soon afterward by Lawrence and his associates, who accelerated protons

in the field of a huge electromagnet until they acquired energies up to 710,000 volt-electrons. This machine is said to be capable of producing protons with energies of 1,200,000 volt-electrons. Two semi-circular plates are enclosed in a vacuum between the poles of the powerful electromagnet. As ionized hydrogen atoms or protons between the plate spiral about in the magnetic field, they are accelerated or speeded up by 2,000 volts every time they make a revolution, thus building up the total voltage to a high value. Higher voltages will be obtained by using more powerful electromagnets. With this (merry-go-round) apparatus Lawrence bombarded carbon with deutons, at 1.5 million volts, the result being the expulsion of a proton and a gain of one unit of mass by the carbon, 7.5 million volts being emitted. Bainbridge has shown that this atom rearranging upholds the Einstein law that mass and energy are interchangeable.

Davis has stated regarding what might be termed the new physical chemistry:

> One might imagine the following hypothetical process. The bombardment of lithium by protons gives high energy alpha particles. By bombarding a mixture of aluminum and lithium with protons the future physicist may start a process similar to but more intense than the more familiar thermite process. The mixture in a certain sense is an explosive mixture. It contains within itself the possibility of maintaining the action if it is once started.

Pokrowski bombarded the heavy metal lead with 140,000-volt x-rays and found that the nuclei of the lead atoms explode and disintegrate under this treatment, particles similar to alpha rays being emitted for more than an hour after they had been exposed to the x-rays for 30 min.

Protons artificially accelerated by a million volts have been found by Tuve to travel 13,400 mi. per sec., by photographing their tracks in a Wilson cloud-expansion chamber. Protons of somewhat higher speeds are noted when paraffin is bombarded with radium's alpha particles.

The experiments of Curie-Joliot, Joliot and Savel in 1932, wherein lithium was bombarded with alpha particles so that a lithium atom of mass seven was hit by and captured an alpha particle, thereby producing a boron atom of mass ten, seems to prove that energy is turned into mass.

Using the deuton as a projectile with voltages up to 1,500,000, transmutations have been produced and alpha rays formed, the

most energetic of the latter ever seen being produced from lithium and traveling almost 15 cm through air.

199. Enter the Neutron.—About 1920, Harkins and Rutherford, working independently, suggested the neutron discovered by Chadwick in 1932 in the rays from beryllium and predicted its properties. The neutron is a close combination of an electron and a proton, being electrically neutral. It has been suggested that the neutron may be formed during the disintegration of matter. It differs but little from a hydrogen atom in mass. It may eventually be shown that the double-weight hydrogen atoms consist of one hydrogen atom and one neutron. Harkins has suggested that the neutron is a new kind of matter with atomic number zero.

It has been estimated that a thimbleful of neutrons would weigh a million tons since they do not push each other apart but lie compactly together, the electron and the proton also being very close together. They easily pass through all known containers because they are neither attracted nor repelled, except by gravity. All other atoms occupy relatively much space because of the relatively great distances apart of the components, something like a stone whirled on the end of a rubber band wherein the distance between the stone and the hand may be relatively great only because of the motion of the stone.

With the discovery of the neutron there arose a number of new theories of how matter is put together, notably by Heisenberg and by Bartlett. Heisenberg visualized the atomic nucleus made up only of protons and neutrons, the number of protons in each nucleus being equal to the atomic number, and he believed that radioactivity was due to there being too many neutrons in relation to protons in the nuclei of the heavier elements which makes them unstable. This theory was said to be the first satisfactory explanation of the mechanism of radioactivity. Alternately adding a neutron and a proton, the latter starting with a helium nucleus (alpha particle), Bartlett predicted the discovery of cobalt of atomic weight 57, manganese of atomic weight 53, and vanadium of atomic weight 49.

Atomic theory at this writing is somewhat upset due to the discovery of the positive electron or positron. This discovery was made right after a scientist had stated that the proton probably was the "last of the fundamental corpuscles of matter." What next? Until the neutron and the positron satisfactorily

have been fitted into their theoretical places, theoretical atomic physics will be somewhat disturbed, but the facts will not be changed. When one experimental physicist makes a discovery that any other physicist can confirm, that is accepted as a physical fact, but theories have to be changed to fit the facts, although sometimes facts confirm theories.

Lauritsen, Crane and Soltan produced neutrons without the use of radioactivity by disintegrating beryllium with artificial alpha particles driven by half a million volts. The resulting neutrons penetrated 2 in. of lead.

Feather caused the artificial disintegration of oxygen by bombardment with neutrons by placing polonium and beryllium at the center of the oxygen-filled chamber to provide the neutrons. The disintegration of oxygen unsuccessfully was attempted by Rutherford in 1919.

200. Discovery of the Positron.—The existence of a positive particle of as little mass as an ordinary electron appeared to have been demonstrated in 1932 by Anderson in cosmic rays at the California Institute of Technology, wherein a number of the results herein mentioned have been accomplished.

Early in 1933, positive electrons were found in cosmic rays by Blackett and Occhialini, at the famous Cavendish Laboratory at Cambridge, England, who also discovered that the positive electron or positron exists for only a fraction of a second before colliding with an ordinary electron.

Dr. Anderson stated in *The Physical Review:*

From the fact that positrons occur in groups associated with other tracks it is concluded that they must be secondary particles ejected from an atomic nucleus. If we retain the view that a nucleus consists of protons and neutrons (and alpha particles) and that a neutron represents a close combination of a proton and electron, then from the electromagnetic theory as to the origin of mass the simplest assumption would seem to be that an encounter between the incoming primary ray and a proton may take place in such a way as to expand the diameter of the proton to the same value as that possessed by the negatron. This process would release an energy of a billion electron-volts appearing as a secondary photon. As a second possibility the primary ray may disintegrate a neutron (or more than one) in the nucleus by the ejection either of a negatron or a positron with the result that a positive or a negative proton, as the case may be, remains in the nucleus in place of the neutron, the event occurring in this instance without the emission of a photon. This alternative, however, postulates the existence in

the nucleus of a proton of negative charge, no evidence for which exists. The greater symmetry, however, between the positive and negative charges revealed by the discovery of the positron should prove a stimulus to search for the evidence of the existence of negative protons. If the neutron should prove to be a fundamental particle of a new kind rather than a proton and negatron in close combination, the above hypothesis will have to be abandoned, for the proton will then in all probability be represented as a complex particle consisting of a neutron and positron.

Dr. Chadwick recently was reported as stating that gamma rays and not neutrons are the cause of positrons. Since Electra had a brother Orestes, Dingle has suggested the name "Orestron" for the positive electron, as many object to the name "positron" on the grounds that it lacks character.

201. Cosmic Rays.—Repeated attempts to eliminate the natural leak or discharge of an electroscope have proven impossible despite the use of the most perfect insulators and the entire absence of ionizing radiations of known types. Lead shields, several feet in thickness, have been used completely to surround the instrument. These facts indicated that there exists an unusually penetrating radiation of feeble intensity.

Electroscopes and similar indicating and recording devices have been carried to points near the two poles of the earth, at the equator, and at various other latitudes. They have been sent up into the air in sounding balloons to altitudes of over 20 miles, and have been carried to altitudes of 25,000 ft. by airplanes in various localities and on high mountains in various parts of the world, as well as to depths as great as a thousand feet in lakes filled with waters derived from snow in regions free from radioactive minerals. All experiments show that the rays come from above the earth. Hence they have been named cosmic rays. Outstanding among the various investigators are Millikan and A. H. Compton.

While cosmic rays will pass through many feet of lead at sea level, it has been found that their intensity at 25,000 ft. is about 21 times that at sea level and still increasing, but one inch of lead reduces the intensity by 40 per cent.

During his ascent in his aluminum gondola during the summer of 1932, Piccard observed with his apparatus that while few cosmic rays come sidewise at the earth's surface, at an altitude of about 10 mi. there was no difference between the number of rays passing horizontally and those passing vertically.

Day and night conditions, particularly at high altitudes, also are said to show changes in cosmic-ray intensity.

Cosmic rays ionize the air and other gases. Compton reported the effects of cosmic rays on chambers full of air, nitrogen and other gases. He found that while such ionization usually increases with pressure, the conductivity of the gas does not increase after 140 times atmospheric pressure has been attained. He believed that the ions formed by the rays readily unite at high pressures because they are so close together. The smaller the time they are separated the smaller the relative conductivity. Compton and his associates also noted a variation of ionization with temperature, but he has suggested that the foregoing may be the explanation of what has been thought to be a real daily variation in the intensity of the cosmic rays.

While authorities agree that there are no significant variations in cosmic-ray intensity with longitude, there is much difference of opinion regarding the variation with latitude, especially at sea level. Experiments by Millikan indicated that cosmic rays bombard the earth with equal intensity from all directions, whereas the experiments of Compton indicate that the intensity is greater with increasing distance north and south of the earth's equator.

In the experiments of Johnson and Street, wherein the intensity of the cosmic rays was measured at an angle of 30 deg with the vertical in the magnetic north, south, east, and west directions, three Geiger-Müller counters were used as a telescope and each cosmic ray had to pass through each counter in succession before it was received. It appeared that the cosmic rays are more intense in the north and south directions than in the east and west directions, at least at 40 deg north latitude. If the findings of Johnson and Street should become generally accepted, it would tend to show that cosmic rays are particles and not electromagnetic rays, since they would then be known to be deflected by a magnetic field which does not occur in the case of short radiation like light, x-rays and gamma rays.

In 1931, Mott-Smith and Locher discovered the straight paths along which cosmic rays travel. Their paths could be seen in a Wilson cloud-expansion chamber where, in a strong light, they appeared as a train of water droplets. As each track was formed, a Geiger-Müller counter simultaneously responded. They believed the cosmic rays to be particles or corpuscles.

In 1932, Locher photographed the tracks and found that they occur in groups of two or three, apparently radiating from one point, more often than could be accounted for by chance. He concluded that the incoming cosmic rays are photons or light-like rays which, striking the air-atom, simultaneously eject two or three electrons and send them flying along the tracks photographed.

At the meeting of the American Association for the Advancement of Science at Atlantic City in 1932, Johnson arranged Geiger-Müller counters in such manner with neon flash lamps that whenever a cosmic ray hit one of them a lamp flashed. By using 58 lamps, the direction from which the rays came was shown by a streak of light. He called the device a hodoscope (Greek for "way" and "to see").

202. Origin of Cosmic Rays.—In an endeavor to trace the origin of cosmic rays it is imperative that the question of their intensities at different latitudes and altitudes definitely be known. That is why so many scientists travel to various points on the earth to experiment.

Based upon his findings that cosmic radiation bombards the earth equally from all directions at sea level, Millikan has suggested that the cosmic rays may be due to the synthesis or putting together of heavy elements out of hydrogen or helium in the depths of the universe. On the other hand, Compton has stated that his measurements indicate a uniform variation with latitude, showing a minimum at or near the equator and increasing intensity toward the north and south poles.

Both of the above authorities appeared to agree that very active electrified particles discharge the sensitive electroscopes used in detecting the effects of cosmic radiation, but Compton considered them the original rays whereas Millikan believed them to be secondary radiation. Millikan stated that differences in cosmic-ray readings at high altitudes might be due to a modification of the earth's magnetic field, but the rays that get down to sea level are so hard that this field does not affect them.

More recently Compton has been quoted: "Cosmic rays may be satisfactorily explained if we suppose the cosmic rays to consist of electrons originating some hundreds of miles above the surface of the earth in the upper atmosphere. It seems very difficult to reconcile with our data any of the alternate hypotheses that have been suggested." He also is quoted as stating that

there is still the possibility that a portion of the rays consists of electrons from outer space.

Millikan has pointed out, on the other hand, that "All observers agree that the immediate agents through which cosmic rays make their presence known are charged particles moving at such high speed that they disrupt atoms along their path. Over six hundred photographs have been taken during the past year (1932). They show the rays to be of enormous energy. They range from 40 million to 1,000 million volts, at least a hundred times larger than any that have been measured previously. The voltage below 500 million predominates. This has an important consequence, for it means that all those of less energy than 500 million volts must be secondary rays, because charged particles with energy of even 1,000 million volts could barely penetrate the atmosphere." He showed photographs with tracks springing out of lead but none entering it. Only photons could thus enter the lead without their tracks being observed. He believed that the primary rays at high altitudes are photons having energies in the neighborhood of 25 million volts.

According to Blackett and Occhialini, there is evidence that matter is being created out of radiation, right here on earth, out of light and cosmic rays only in the neighborhood of an atomic nucleus, in the form of a pair of electrons—a negatron and a positron.

The cosmic-ray hiss or static received on a short-wave radio receiver, tuned to a wave length of 14.6 m, by Jansky, has its source near the center of the Milky Way galaxy, as determined by Shapeley, toward which the solar system is moving with respect to the stars.

203. Further Experiments and Theories.—During the expedition of the *Vega* in 1878, Nordenskjöld observed a portion of a ring or aurora light above the polar region. In 1932 Dauvillier placed a hollow iron sphere with a magnetizing coil inside a hollow sphere that represented the earth. The whole was then placed in a large glass bulb (the air pressure being about a millionth of an atmosphere) also containing a hot cathode from which a stream of slow electrons of 200 v energy was ejected and then deflected by the magnetized sphere. As these electrons struck the air-atoms they produced secondary electrons which formed a ring of aurora light around the polar regions. From this experiment

Dauvillier concluded that cosmic rays are electrons shot out from the sun.

According to Locher, x-rays are produced in the gas of a detecting chamber by the passage therethrough of swiftly moving particles like electrons. Compton is reported to have suggested that electron cosmic rays may produce photons in the earth's atmosphere, just as electrons produce x-rays in an x-ray tube, to account for the penetrating radiations found in the depths of lakes. The shorter the wave length, the "harder" and more penetrating the radiation.

In the experiment reported by Bothe, referred to in Art. 198, wherein he and Becker produced super-gamma rays, the rays really are to be considered as soft cosmic rays as penetrating as 14 million-volt x-rays, according to one theory. Their penetrating power is so great that after passing through 3 in. of iron they have lost only a third of their intensity.

204. Disrupting the Atomic Nucleus with Cosmic Rays.—In 1932, Anderson discovered that cosmic rays knock both electrons and protons from the nuclei of oxygen and nitrogen. When this occurs and these high-speed particles of electricity and matter travel through a magnetic field, they leave curved tracks of water droplets in the Wilson cloud-expansion chamber that Anderson has photographed. The electrons' track is of 140 million volts energy, while that of the proton is of about 70 million volts.

In Anderson's experiments, the emitted electrons travel at speeds equal to 99.9 per cent of the speed of light, while the protons travel at about half that speed. Thus cosmic rays continuously must be converting nitrogen into hydrogen.

It has been suggested that cosmic rays are neutrons which cannot be deflected by magnetic fields, but which can smash into the atomic nucleus with much more energy than can a positively charged particle because there is no repulsion between the atomic nucleus and the proton.

It also has been suggested that perhaps the mutations or biological transformations in plants and animals which occur in nature have been due to the actions of cosmic rays on living matter. Anderson's discovery would seem to confirm this theory in view of the known mutations caused by x-rays, as referred to in Art. 185.

In his address before the summer meeting of the American Association for the Advancement of Science at Chicago in

1933, Dr. Millikan announced that he and his associates had determined, within a small percentage of error, that the mass of the positron is identical with that of the negatron or well-known electron. He also presented evidence that seems to indicate that elements heavier than uranium, atomic number 92, are being created in the interstellar spaces. He has found that cosmic rays come in intensities ranging from energies of 100 million to 2.7 billion volts.

Dr. Millikan also stated that the Einstein equation and the Aston curve are working so well in other nuclear results that it is at least natural to apply them to the cosmic ray, the energy of which falling into the earth is approximately one-half of the total energy coming from the stars. Since the positrons can come only from the atomic nucleus, very high energies are required to drive them out. The outer part of the atom consists entirely of negatrons. Hence the high-energy rays penetrate the outer shell of the atom without harming it and attack the nucleus, while the low-energy rays strike the outer shell as well, thus accounting for the much larger proportion of negatrons when the energies are below 100 million volts and the equality of numbers and distribution of negatrons and positrons at the higher energies.

CHAPTER XXV

OSCILLATIONS AND WAVES

The genius who made the first bow and arrow not only produced an engine wherein he could store potential energy through muscular contraction later to be converted into kinetic energy at a high time rate and thereby project his arrows or spears at much higher velocities, with much greater penetration and to consequent greater distances than he could throw them, but he also produced an oscillating system of such frequency as to emit an audible musical note—the "twang" of the bowstring. It is not difficult to visualize the evolution of string musical instruments from this crude beginning. Now we have various electronic musical instruments based upon changes in self-inductance and capacitance.

The mechanical and electrical laws of oscillations are very similar. Just consider self-inductance as inertia and the reciprocal of capacitance, that is, elastance, as tension and the two mathematical laws become identical, the oscillation frequency being proportional to the square root of the ratio of the tension to the mass. Much as an oscillating string sets air waves in motion to carry the sound to a distant point, so does the oscillating electricity in a wire send forth the ether waves of radio to the remote places of the earth. This oscillatory principle is so general that it has many applications in industry, as discussed in Art. 115.

205. Music is produced in eight fundamental sounds, the fourth octave C sound being 256 double vibrations or cycles per second, the fifth octave C having double that frequency, or 512 cycles per second, and so on. Interposed between these first and eighth sounds are the second of 288 cycles; third, 320; fourth, 340; fifth, 384; sixth, 420, and seventh, 480 cycles per second. Taking the first sound of 256 cycles per second as unity, the ratios of the other sound frequencies to it are: Second, $9/8$; third, $5/4$; fourth, $4/3$; fifth, $3/2$; sixth, $5/3$; seventh, $15/8$, and eighth, 2. Hence their relative wave lengths are 1, $8/9$, $4/5$, $3/4$, $2/3$,

$\frac{3}{5}$, $\frac{8}{15}$ and $\frac{1}{2}$. Subtracting these ratios from 1 gives 0, $\frac{1}{9}$, $\frac{1}{5}$, $\frac{1}{4}$, $\frac{1}{3}$, $\frac{2}{5}$, $\frac{7}{15}$, and $\frac{1}{2}$.

Musical instruments may be tuned by the beat method. When two strings vibrate at almost equal frequencies, the sound waves alternately and periodically reinforce and oppose one another, thereby producing the effect of a note of a lower frequency equal to the difference of the frequencies of the two notes being compared. This is the well-known heterodyne principle employed in radio.

206. Spectra.—Since the hydrogen spectrum is that of the simplest atom, atomic number 1, the relationships between its lines observed in the spectroscope have been correlated in many instances. Three distinct series of lines have been recognized, namely, the Lyman, the Balmer, and the Paschen series. Each of these series apparently has an infinite possible number of lines according to the formulae that account for the measured lines, all the way from the lowest possible frequency up to the highest.

One of the most important constants in nature is the Rydberg frequency. Its value is 3,277.5 trillion cycles or waves per second. This makes the corresponding Rydberg wave number 0.1093 million waves per centimeter. The ratio of these two constants is the velocity of light. These constants not only hold for the hydrogen spectrum but for all other elements whose spectra have been expressed by formulae.

The rule for finding the oscillation frequency of a hydrogen spectral line in any of the above series is to multiply the number 3,277.5 trillion by numbers obtained as follows: For the Lyman series, subtract the squares of $\frac{1}{2}$, $\frac{1}{3}$, $\frac{1}{4}$, and so on, from 1, thus obtaining $\frac{3}{4}$, $\frac{8}{9}$, $\frac{15}{16}$, . . . For the Balmer series, subtract the squares of $\frac{1}{3}$, $\frac{1}{4}$, $\frac{1}{5}$, . . . from $\frac{1}{4}$, thus obtaining $\frac{5}{36}$, $\frac{3}{16}$, $\frac{21}{100}$, . . . , while for the Paschen series, subtract the squares of $\frac{1}{4}$, $\frac{1}{5}$, $\frac{1}{6}$, . . . from $\frac{1}{9}$, thus obtaining $\frac{7}{144}$, $\frac{16}{225}$, $\frac{27}{324}$ . . . To find the corresponding wave length, divide the velocity of light by the oscillation frequency.

It is interesting to note that while the "music of the atoms" tends to exist in infinite series, the chemical natures of the atoms cause them to be classified in octaves much as the notes in ordinary music.

Bohr accounted for many lines in the hydrogen spectrum by assuming that the single electron described orbits about the proton nucleus and by specifying the orbits in terms of dynamical,

instead of geometrical, quantities and that the angular momentum must be a multiple of a quantum (Art. 129) divided by 6.2832. He called this principle quantization wherein the "quantized states" were called energy levels, all of which were negative and had the relative positions -1, $-\frac{1}{4}$, $-\frac{1}{9}$, and so on. In radiating energy the atom would contract dynamically, that is, the electron would go to the next energy level and would jump down to it suddenly, thereby radiating the difference of energy between $-\frac{1}{4}$ and -1, that is $\frac{3}{4}$, which means that the wave length of the light would be $\frac{3}{4}$ of the Rydberg wave number in this particular instance.

The meaning of the term "energy level" appears to be made clear by the experiment of Franck and Hertz, wherein they studied the light from a mercury-vapor tube through a spectroscope at different voltages, first one line and then another appearing only at critical voltages until all finally appeared at the highest voltage used.

The Bohr atom was very useful in describing the reasons for spectra and it accounted for many spectral lines, especially in the case of hydrogen. While Bohr's theory had no rational basis besides the observed facts in spectra relationships and that the energy of light comes in "bundles" or quanta, it worked and was the first step in the discovery of the new quantum theory of Heisenberg. The quantum itself was discovered by Planck at the beginning of the present century.

207. Radio Springs from a Master Mind.—From its mathematical conception to its practical application, the romance of radio was unparalleled until recent years.

Astronomers supposed that light passed instantly from the source to the observer, until the year 1675 when Roemer accurately observed the instant at which one of Jupiter's satellites passed into Jupiter's shadow and, knowing the mean time interval between such eclipses, calculated the exact instant at which a given eclipse should occur when the earth had arrived on the opposite side of the sun six months later, at which time he made another observation and discovered that the eclipse occurred 966 seconds later than he had calculated. Hence he considered that this delay represented the time required for the light to travel across the earth's orbit.

Since sound was known to be a form of wave motion, a wave theory of light was developed by Huygens (1629–1695), but the

corpusculatory or particle theory of light was the one most accepted until about 1800. While corpuscles or particles could be shot through a void, there must be something in space to form light waves, just as there must be water if there are to be any waves in water. So Huygens invented the ether as a hypothetical something wherein the waves in which light was assumed to be propagated might be formed.

Maxwell (1831–1879), following up Faraday's theories and experiments, balanced the mechanical force of repulsion due to two unit electrical charges in the electrostatic system of cgs units against the force of mutual repulsion of two equivalent magnetic poles in the electromagnetic system, by measuring the current strength necessary to produce the latter, and found the electromagnetic quantity of electricity (the abcoulomb) to be 30 billion times greater than the electrostatic unit (statcoulomb). Now this quantity is the velocity of light in centimeters per second; Maxwell, therefore, used his discovery as a basis for his celebrated equations of the electromagnetic theory of light which ultimately resulted in wireless telegraphy and telephony, or modern radio.

Maxwell's work of 1864 stands out as a shining example of how a mathematical theory with a sound basis sometimes produces the most amazing, yet practical results—after other men have developed the practical side of it. His theory has explained almost all light phenomena, but not quite all. Light is known to travel in wave form. The energy of light, however, is known to come in "lumps" or quanta. Maxwell's theory indicated that all electrical charges in motion produce magnetic stresses in the ether, to which he was able to ascribe definite properties through mathematical symbols and relationships. Thus so elementary and primordial a "sub-substance" was evolved from nothing more tangible than geometry with accurately known facts as the basis. That the ether is considered as something more than a void is the belief of many physicists (Chap. IX), while others believe it nonexistent.

Maxwell's work indicated that oscillating electrical charges should establish electromagnetic waves in the ether and suggested an experiment that was carried out in 1888 by Hertz who generated high-frequency electrical oscillations with rather crude apparatus consisting of the equivalent of a condenser and a coil containing self-inductance in an electric circuit, much as in more

modern equipment. By means of a resonator consisting substantially of a nearly closed loop of wire with a microscopic adjustable air gap in which sparks could be observed under favorable conditions, Hertz confirmed Maxwell's belief that electromagnetic waves possessed many of the properties of light waves. Thereafter many experimenters improved the apparatus and Lodge operated a wireless telegraph over small distances. But Marconi put wireless telegraphy on a commercial basis.

A simple and partial explanation of the production of radio waves may be made by assuming a wire or antenna perpendicular to the surface of the earth. High-frequency oscillations may be made to travel up and down this wire because the upper part alternately and periodically becomes electrically charged and discharged, the earth being the opposite terminal. When the current is flowing at its maximum velocity, the associated magnetic flux also is at its maximum magnitude and is moving outward from the wire over the surface of the earth, as well as in other directions, at the velocity of light. When the current reverses, and at the instant just before it starts flowing in the opposite direction, its strength is zero and no magnetic flux is being produced—so the wave becomes completely detached from the electricity in the wire and travels onward as a radio wave. When it arrives at another antenna it momentarily becomes linked therewith, thereby establishing a difference of potential and a transient electric current in the wire which develops into regular oscillations in the presence of a train of waves.

208. Radio-oscillation Frequencies, Wave Lengths, and Ranges.—The radio-broadcast range is from 550 kc per sec. (545.1 m) to 1,500 kc (199.9 m), while frequencies as high as 30,000 kc (10 m) and as low as 10 kc (30,000 m) are commercially used in long distance communication.

Besides the so-called ground waves, which travel over the surface of the earth when they become detached from the transmitting antenna and follow the curvature of the earth, being bent around mountains and larger obstacles up to 100,000 kc (3 m), there also are the so-called sky waves which are emitted straight upward from the transmitter at frequencies between 700 kc (428.3 m) and 100,000 kc (3 m), and cause fading and interference through being reflected by the Kennelly-Heaviside layer. It is obvious that the sky waves arrive at receivers at

different instants from the ground waves, thereby causing interference (also see Art. 50).

As the frequency is increased and the wave length thereby decreased, the ground waves are more and more absorbed. Between 2,000 and 3,000 kc the ground-wave distance falls from 80 to 60 mi.; between 7,000 and 8,000 kc it is 45 mi., and at 16,000 kc it has fallen to 30 mi.

Sunlight and atmospheric conditions have pronounced effects on radio reception, so that generally it is much better at night; there are, however, exceptions, depending upon the wave lengths. For 100 kc (3,000 m) the maximum range is about 6,000 mi.; 200 kc (1,500 m), 1,500 mi.; 500 kc (600 m—SOS call), 1,000 mi.; 900 kc (333.1 m), 300 mi.; 1,500 kc (200 m), 200 mi.; and for 16,000 kc, 30 mi.

Between 2,000 and 3,000 kc, the summer-night range increases from 350 to 1,500 mi., and the winter-night range increases from 1,500 to 4,000 mi. Between 7,000 and 8,000 kc, the winter range is 4,000 mi.

At still higher frequencies and corresponding shorter wave lengths, as below 3 m, the sky wave no longer is reflected, but the ground wave is highly absorbed. The sky wave may come back to earth a hundred miles or more away from the transmitting station without affecting radio receivers in the intervening territory. This distance is called the skip distance. Between 7,000 and 8,000 kc, the winter skip distance is 400 mi., and at 18,000 kc it is 1,000 mi. on a winter day.

At 23,000 kc the winter wave is not reflected, while at 60,000 kc (5 m) the waves travel in straight lines to the horizon. Three-meter waves have all the characteristics of optical light. It is possible to-day to produce electromagnetic waves having frequencies up to that of visible light by special radio methods. Reflectors have been employed to cause the rays to leave them in practically straight lines.

209. Ultra-short Radio Waves.—In 1919, Whiddington discovered that gassy triodes could, under certain circumstances, be made to generate oscillating currents of very high frequency. Barkausend and Kurz, in the same year, produced oscillations having a wave length of 1 m, with vacuum tubes having cylindrical concentric elements and with the filament passing through the geometrical axis of the grid and plate, by varying the grid voltage; their theory was that with a relatively high positive potential

on the grid and a low negative potential on the plate, electrons emitted from the filament would be attracted to the grid, but because of their high speed and consequent momenta many would pass clear through the interstices of the grid toward the plate from which they immediately would be repelled, thus completing one cycle between the grid and the plate. Scheibe, Gill and Morell, and others since have produced high-frequency oscillations by various methods. On March 31, 1931, communication across the English Channel was maintained on a wave length of 18 cm by means of parabolic reflectors using only 0.5 w of power. Ultra-short waves are employed in radio telephony and the operation of radio typewriters, and probably will be used in broadcasting and television.

210. Standing Waves.—When waves are reflected, as sea waves from a breakwater, there is a series of waves traveling in opposite directions. Hence at certain places the crests meet and the water alternately moves high up and deep down. At other places the oncoming wave is at the top when the reflected wave is at the bottom, and a node is formed so that the water permanently remains at its mean level at the nodes, while the crests rise and fall midway between the nodes. These are called standing waves.

Radio waves are reflected from the open ends of wires. Thus if two parallel wires, called Lecher wires, each are connected at one of their respective ends to the respective terminals of a source of high-frequency oscillations, standing waves will be produced in the wires and the nodes may be found by means of a crystal detector and a galvanometer. The distance between nodes is half the wave length. The crystal detector is a rectifier which changes, through thermal action, the oscillating current into a direct current by eliminating the current in one direction.

211. Effects of Short Waves on Living Organisms.—Numerous experiments of this nature have been performed. Schereschewsky implanted tumors in mice and treated them by placing them in electrostatic fields, as between the plates of an air condenser, with frequencies ranging from 8,300 to 150,000 kc per sec., produced with ordinary triodes. Although no free electrons could enter or leave the mice in the technique employed, results were favorable in many cases, with the exception of the shedding of hair.

Whitney has made many experiments with very short waves, one description being by Page in the July, 1930, number of *Electronics*, wherein mice lost their tails; cold feet were heated; insects were killed; metals were melted; rats responded to invisible heat; moisture was driven out of porcelain; and hibernating fruit flies revived in zero temperatures.

Radio heating has been substituted for malaria treatment which was given paresis patients to induce a curative fever in them. Such machines are called "artificial fever" machines, Schliephakes being a noted experimenter in this field. The patient is placed between the plates where an exposure to the short waves for an hour or more will produce an increase in body temperature from 98.6 to 104 or 105 deg.

Using waves of 3 m with a power of 1.5 kw, Schliephakes found that the waves immediately killed flies and caused the slower deaths of mice, rats, and guinea pigs.

Using a generator producing waves of from 25 cm to 1 m in length, Pape has claimed that in his house food several months old was maintained in an odorless and undecayed condition, the radius of his transmitter being about 20 ft.

There is another form of radiation, called M-rays, mitogenetic rays, or Gurwitsch rays, which are given off by rapidly growing tissue, having wave lengths of about 3000 Å, and which will pass through quartz but not through glass. Recently, Rajewsky devised for their measurement a special form of Geiger counter having a thin sheet of cadmium between the special wire and the quartz window. When the rays fall on the cadmium, electrons are released.

212. Radiothermy.—High-frequency currents are directly applied to tissue, as in electrotherapy and surgery. When the frequency is of the order of a million cycles per second, one may take hold of the electrodes of such a machine with two 50-w lamps connected in series with the body and they will be brightly illuminated without the one holding the electrodes feeling any sensation but that of heat, which soon becomes intolerable in the wrists when the current strength is about 1 amp. Such a current strength quickly would kill if it came from a power circuit, for example. The cells of the tissue are electrolytic in character, but the ions do not have time to move far enough in any direction to cause neuromuscular contraction when the frequency of the current is so great.

Tesla first introduced high-frequency currents into therapeutics in the United States in 1890, about the same time as did D'Arsonval in France. The treatment of boils, carbuncles, and arthritis by radiothermy may become an application of the fever machine in the future.

The radio knife operates on the principle that the heat due to a relatively great current density at the point of the cutting needle causes minute steam explosions in the tissue, thereby causing it to separate as though cut by a knife. The author's experience in the development of such machines and their use in major operations in hospitals under the direction of surgeons are described in full in the October, 1930, number of *Electronics*.

213. Talking over Light Beams.—Light beams are modulated much as in radio. In fact, modern radio-beam transmission operates on identically the same principle so far as the projection of the beam is concerned. Bell demonstrated the photophone many years ago, but the good qualities of present-day amplifiers have made it possible to revive older methods of communication for transmission over a distance of 30 mi. It is easier and more economical to produce long red waves of 0.0001-cm wave length than it is to work with radio waves a few centimeters in length. Whether or not it will pay to produce by radio methods waves of extremely short length, when all one has to do is to electrically heat a mass of metal to act as a radiator, is a question.

It is obvious that any kind of beam which will affect a photoelectric cell may be employed for communication and distant control.

CHAPTER XXVI

THE ELECTRONIC PAST AND FUTURE

Man's range of percéption, extending from the electron to the remote nebulae of space, truly is remarkable. Much as the orbits of the planets Neptune and Juno were calculated before those planets actually were discovered, so also was the electron predicted, although it never has been and never will be seen by man, one of the reasons being that the light necessary for its observation would knock it out of the way.

In man's aim to find the ultimate, ideas have changed very much indeed. At first the earth was flat, with the sun, moon and stars floating across the dome of heaven. Then the earth was assumed to revolve about the sun, and it was found that other planets were doing likewise. The atom was isolated as an entity and assumed to be solid. Then the atom was found to consist of electrical charges which were assumed to simulate the solar system with a positively charged group as the "sun" and electrons describing orbits about it as "planets."

But the electrons, and then the atoms, practically vanished into waves. Now we have not only electrons and protons as building blocks but neutrons and positrons as well, with individual magnetic poles predicted by Dirac. While it is not difficult to conceive the neutron as a close combination of electron (or negatron) and proton, what is the proton made of and how is it put together? What is a negatron (electron) and what is a positron? Of what are they composed? Noted physicists are reported to be looking into the matter.

214. Looking Backward.—It was stated in Art. 2 that the field of application of electronic devices has no end and that the electronic art has only begun. To appreciate this, let us picture ourselves back in Faraday's and Henry's time when electromagnetic induction first was discovered. Who ever could dream of all the marvelous benefits that have arisen through the applications of inductance, capacitance and resistance? It is doubtful whether even the keen-minded Maxwell could foresee commercial

radio. It took men like Edison and Marconi to make practicable the discoveries and predictions of the scientists.

Now let us picture ourselves exactly where we are to-day and try to visualize what present and as yet unborn Edisons and Marconis will accomplish through the practical applications of electrons, protons, neutrons and positrons in, for example, attacking the atomic nucleus, producing unlimited power, and perhaps transmuting lead into gold. Let us also try to visualize what the machines and devices of the future will look like and whether or not power will be broadcast by radio or whether it will be converted on one's premises, as in one's electronic kitchen range.

The absurdity of such an attempt at visualizing the future, except in a very general way, is evident when we realize that, perhaps, we are not Edisons and Marconis. Not so many years ago people said we never would be able to fly. To-day we fly. While the scientist Lodge already had the wireless telegraph working over small distances, it still needed Marconi to make it bridge even five miles and then the ocean. We look into the future by looking backward. We see the generalities of the future reflected in the mirror of the past, but the details ever are blurred. One thing we see is that engineering appears to lag a long way behind scientific discovery, but this evidently is not the sole fault of the engineer. There are reasons why this development must be slower.

Although electric currents long have been employed commercially and high-frequency carrier currents have been used for communication and control over power transmission lines, as well as over telegraph and telephone lines and cables, an entire department of the electronic art, thus far hardly touched, awaits development in connection with solid conductors, resistors and crystals.

The effects involving heat and electricity are the thermoelectric effects of which there are three major kinds. If a bar of lead and a bar of zinc are joined together, end-on, and then are heated at the junction, a steady electron current will flow from the zinc to the lead and through a connecting wire from the lead back to the zinc. If the two metals are left cool and an external difference of potential is impressed upon them to cause an electron current to flow from the zinc to the lead, the junction will be further cooled, whereas if the electron current is made to flow

from the lead to the zinc the junction will be heated. This is known as the Peltier effect.

When a rod of antimony and a rod of bismuth are joined together, end to end, and this junction is heated, then, if the opposite ends of the rods are brought together and that junction is kept cool, an electron current flows from the antimony to the bismuth across the hot junction and from the bismuth to the antimony across the cold junction. This is the Seebeck effect.

The Thomson or Kelvin effect consists in the transportation of electrons with a current of heat, and *vice versa.* If a ring of wire is heated at one point, electron currents tend to flow in opposite directions but oppose each other, that is, the two pressures oppose each other, but if the wire is kept cool on one side of the hot point an electron current will flow in that direction, that is, in the direction of lowest pressure. If an electron current is made to flow in a wire containing a hot point, through the application of an external difference of potential, the electron current will carry the heat along with it, as may be observed in an iron wire.

The thermoelectric effect (Peltier) is employed in the thermocouples for measuring temperature and detecting heat rays (end of Art. 153).

The effects of electricity, heat, and magnetism, as in the Hall, Nernst, Ettinghausen, and Leduc effects, eventually should find useful applications. When a thin strip of metal is placed over the north-seeking pole, for example, of an electromagnet and a difference of potential is applied to the ends of the metal strip so that an electron current flows lengthwise in it, there is found to be a difference of potential between its sides; a difference of temperature between its sides; a change in the electrical conductance (hence in the resistance), and a change in the thermal or heat conductance of the strip. If the two ends of the metal strip are maintained at different temperatures (instead of at different potentials) so that a current of heat shall flow lengthwise in the strip over the electromagnet, the same four phenomena are observed, making eight phenomena altogether, showing that there is an intimate connection between currents of heat, currents of electricity, and magnetism. In bismuth, at least, a current of heat produces the same effects as a current of electrons. These effects are described more fully and in a simple manner in Fournier d'Albe's "The Electron Theory."

Reboul (Art. 188) has shown that high-resistance materials behave much as vacuum tubes in the production of x-rays, selenium exhibits an internal photoelectric effect (Art. 132), thereby acting much as a vacuum photoelectric tube, while the barrier-layer photoelectric cells (Art. 139) behave in an analogous manner.

In view of the rather belated useful applications of the photoelectric effect it would appear that, in due time, means will be devised or discovered whereby these effects also will be made generally useful. It may be recalled that the Edison effect (Art. 55) was a mere curiosity from about the year 1883 until the advent of the Fleming valve (Art. 56), which eventually made modern radio possible.

In this general connection it may also be recalled that a simple crystal detector, usually comprising a crystal, as galena, with a metal contact, as a cat-whisker wire, may be as effective, as a radio rectifier or detector, as a Fleming valve when coupled directly with the antenna. The description of the general form of the crystal detector is very similar to that of the photronic cell (Art. 133).

Furthermore, there are numerous other effects that never have been given practical applications, at least not on a very large scale. There are plenty of opportunities for modern Edisons and Marconis, and these opportunities increase with each new discovery.

215. Chance and Causation.—We come into this world, and consciousness of it, of ourselves, and of others gradually dawns upon us. The chances are about even as to whether newcomers will be born to grow up in the men's world or in the women's world. One's point of view certainly is affected by this chance. One does not even select one's parents. Women live in the women's world and men live in the men's world, yet both live in a common world—a world of chance in many respects; a world of concrete cause-and-effect laws in others.

We are largely ruled by the dead, the men and women who established our customs, laid out our cities, streets, and roads, and built our railroads and systems of communication. Most of these things were here when we arrived and we simply take them for granted. We do certain things and follow certain routes, all because men and women now dead did substantially the same things. We even strive to follow the teachings of men

who died thousands of years ago. These are some of the concrete cause-and-effect things. Time and space become conspicuous in consciousness when we think of things like these.

Our ancestors left us an edifice upon which we continue to build. Sometimes, however, we rebuild portions of the old structure because, in the light of new observations, old portions become obsolete and are obstacles in the path of progress, although they may have served well as scaffolding and later may be required as we learn through experience. Idealistic laws sometimes are repealed. Knowledge is like a coral reef—what is left from the work and experiences and theories and discoveries of those who have passed on. We live and work for posterity but, like our ancestors, we all make mistakes.

Our future work is guided largely by experience. If we have not had the personal experience, we must depend upon those who have had the experience, or else resort to chance. In cases of dire extremity, we even may resort to magic. Many a scientist as well as a business man woos the humble "hunch" and finds that it works after giving the matter at hand much consideration. But that kind of a hunch may have much sound sense back of it.

216. Chance Follows Definite Laws.—Those who plan the growths of cities and great public utilities combine experience and chance. Business men do substantially the same thing in planning for the future. If things went about so and so during such a period and under such conditions, they should come out about so and so during the next year or decade, as the case may be. This may be only good guessing in some cases, but the chances can be, and usually are, determined with great exactitude by mathematical computation, provided the premises are correct and enough entities enter into the case, as will be understood presently.

Life insurance companies know the average age at which a given group of insured will die. Some may die at 40 and some at 80, but the company does a successful business based on averages. The law of averages is the basis of "honest" gambling. A proprietor only has to know the averages of his various devices in order that he may list the chances on a profitable basis. Sampling is another example of the application of the laws of chance or probability.

No one can tell how a coin which has been flipped and thus spun in the air will land, but anyone can make two guesses, one of

which will be right, unless it should happen to land upon its edge. A cube has six sides; the probability of a guess as to which side will land upward in any trial is not so accurate, but all six sides tend to land upward an equal number of times after a great many throws. This has been tried with six dice thrown simultaneously ten thousand times, when all had "come up" so similarly that the variation was only a fraction of 1 per cent.

Assume that millions of insects, driven before a westerly wind, are attacked by millions of birds that dart back and forth, upward and downward, and in other directions in pursuit. Every bird may be doing something different at any instant, yet we may count the number of birds that pass through an imaginary vertical plane every minute, as they drift in an easterly direction, with the same exactitude as we can ascertain how many electrons drift through any plane in the cross section of a conductor every second.

217. The Elusive Electron.—An experienced billiard player knows in advance what will happen to both billiard balls when one strikes another, but no one knows what will happen when one electron strikes another. When an electron is shot at an atom, the result may be an x-ray, it may be a secondary electron, or it may be just heat. But when a very large number of electrons is concerned, as in an electric conductor, one knows what the average current strength will be, for Ohm's law deals with averages. Hence what seems concrete to us, as in the well-known mechanical laws, are only average conditions that do not hold at all for the ultimate particles of matter. Thus the quantum laws tend to become the same as the well-known mechanical or classical laws when large numbers of electrons and atoms are concerned.

When one deals with individual electrons, one must resort to the laws of chance, that is, to probability, and that is how mathematical physicists are studying the electron with the wave mechanics and quantum mechanics, for the electron has a wave aspect as well as a particle aspect, the quantum being the only universal connecting link between the two aspects. To find the wave length of a particle, divide the quantum by the momentum of the particle. This rule also holds for photons, atoms, molecules, protons, and other bodies.

In 1927, Davisson and Germer were studying the scattering of electrons from a sheet of nickel, when their apparatus broke

and the necessary heating of the nickel in making repairs changed its surface into a substantially perfect crystal. Upon resuming their experiments, the electrons were diffracted, thus showing that they are accompanied by waves, as predicted by de Broglie and by the new quantum theory. Soon afterwards, G. P. Thomson invented a somewhat different method of studying the diffraction of electrons.

In an address reported in *Science* (June 23, 1933), K. K. Darrow stated in part:

> Suppose we send a beam of electrons against a crystal. The crystal is an assemblage of atoms regularly arranged. Each atom is a collection of electric particles roaming in vacant space. The sizes of these particles are so small compared with the spaces between them that each atom may be regarded for the present purpose as a narrow empty region where there is an electric field (and also a magnetic field) varying rapidly from point to point. The crystal is an assemblage of these narrow concentrated fields, tens of millions of them to the linear inch. We might say that it is a region of space occupied by a rhythmic pattern of field strengths. This is traversed by the electron stream, which behaves in a most remarkable way, as Davisson and Germer found. It behaves as though it were attended by a train of waves, and the crystalline pattern seized upon these waves and guided them according to the well-known laws of wave motion, while the corpuscles trailed after them.

No matter how complex the situation may be, nature always follows the path of least action, and it can be shown by diffraction that nature always sends out waves as scouts to find the path of least action, the waves cancelling out through interference, except at the places where the action will be the least. Thus nature sends out waves as guides to find the most economical route, as in the mirage, for example. There are no pure waves and no pure particles, according to modern belief.

According to Langer:

> The old controversy between the wave theory and the corpusculatory theory of light is unimportant because either one can be made complete and self-consistent. The same holds with regard to the theory of matter. However, the wave theory has had a certain advantage in the discussion of experiments on diffraction by gratings or crystals both for the optical and the electronic or atomic case. This advantage which was merely in the simplicity of the deduction of the diffraction formulae no longer obtains because with our newly acquired knowledge of the

solid state; an argument originally proposed by Duane can be developed which makes the corpusculatory description even simpler than the other. The important property of a solid body in this connection is that the electrons in it can take on only certain peculiar velocities or momenta. . . . The particle point of view is for many physicists an easier one to visualize and they will prefer to think entirely in terms of particles when they find that no unnecessary complications are involved in such a course. This will make it easier to interpret and devise new experiments . . .

218. The Place of Chance in Scientific Discovery.—Up to the early part of the nineteenth century men knew that steel was magnetized by lightning, and they made many unsuccessful attempts to magnetize steel with electric currents, although they felt certain that electric currents produced magnetism. And they never did succeed in intentionally producing magnetism with electric currents until it was done for them by *chance*, when Oersted just *happened* to notice it. Nobody was smart enough to invent an efficient electric motor, although many able men attempted it. Yet they had one all the time and did not know it (Art. 40).

The discovery of the Leyden jar came about in a manner wholly unsuspected by Musschenbroek and his pupil Cuneus. To their credit, however, be it said that they attempted to fill the jar with the "electric fluid." While the wave nature of the electron had been predicted by de Broglie, its discovery came about through an accident, but Davisson and Germer were quick to note and interpret the effects predicted.

In all such cases, and there are many of them, the discoverers deserve great credit. It is not so important *how* a new and useful principle is discovered as the fact that it has been captured and brought forth from the dim and nebulous unknown world to stand revealed in the light of knowledge, like an unknown specimen dragged by chance from the depths of the sea.

If history is of any value in predicting future events, one may conclude that further great discoveries will be made through accident or *chance*. Perhaps man never may discover how to run his machines with the energy obtained from thimblefuls of matter through its controlled disintegration—by the methods which he now pursues. But still he may discover it by *chance*.

Those who have the best chances of making discoveries are the ones who experiment and keenly watch for results. The old-

time prospector set a good example by using his experience and wits—and then taking chances with his eyes wide open. "Dig and watch" seemed to be his motto. Experimental physics is a powerful factor in scientific achievement.

219. Progress Never Stops.—History has shown in many instances that when a machine has reached its highest stage of development it is ready for the scrap heap or the museum. Each is a step toward something entirely different which will perform the same general function in a much better and more efficient manner. Thus the large Corliss engine reached a stage in its development where it seemed that it could not further be perfected, only to be replaced by the turbine.

The highly perfected electromagnetic mechanisms developed for the control and protection of electrical machinery and circuits likewise reached a stage of perfection which apparently could not be bettered, only to be headed for the scrap heap and the museum in view of the new electronic devices. If history is a guide to the future, as above outlined, it seems evident that these, in turn, will be perfected only to give place to improved devices wherein, perhaps, neutrons, positrons, protons, negatrons and helium nuclei or alpha particles will play important parts. But the men who will accomplish these things may not yet be born.

Mathematical theories have their place and always should be tried out when practicable. Nearly a quarter of a century elapsed after Maxwell expounded his electromagnetic theory of light and suggested that it be tried before it actually was tried out. When Hertz tried it, *it worked.* There have been many such delays between suggestions and actual experiment.

But mathematics is not the goal of achievement. K. T. Compton has called attention to this in so striking a manner that it has been reserved as the closing statement in this volume. It is from an address published in the February, 1933, number of *Electrical Engineering*, as follows:

A crude analogy will illustrate the relative advancement of our present state of knowledge of atoms. Liken the nucleus to a building and the extra-nuclear electrons to a group of pebbles resting on the steps of a fire escape on the outside of the building. As we observe these pebbles, we notice that from time to time a pebble falls from one step to another. We do not understand why it falls; hence we make various attempts to hypothecate some model or mechanism that will explain the dropping of these pebbles. Bohr, Sommerfield, Langmuir

all take their turn, but none of them invents a mechanism that satisfies all of the observations. We become discouraged with model building.

Finally a brilliant young man, Heisenberg, proposes that we do away with models entirely and concentrate entirely upon the observable quantities—the steps, the pebbles, and their falling. He finds a mathematical expression which accurately correlates the height of the steps (energy levels) with the probability that a pebble will fall (radiate) from one step to another. To the mathematician this accurate formulation of the mathematical relationship between the observable quantities is a complete and satisfactory explanation or theory.

The physicist, however, guided by instinct (which is the accumulated wisdom of the ages) rather than by formal logic, is not satisfied. He feels impressed but a bit confused by the logic of the mathematician, and also a bit distrustful. Down in his heart he feels that there must be something more than a law of probability that makes those pebbles drop.

He goes to investigate. He finds the door of the building locked. He pushes; he knocks; he gets help; he rigs up a machine to batter down the door; he makes a small hole through which he sees signs of activity within the building; he builds a bigger and better battering ram; finally he breaks down the door and goes in.

Within the building he finds a huge factory; giant cranes carry around great masses of material; enormous machines press, hammer, and draw this material into various shapes. Stupendous forces are at work. The building shakes, and from time to time a little pebble on the fire escape is shaken down from one step to another.

So, perhaps, sometime may be resolved the peculiarities and puzzles of our present quantum theory—by small and external manifestations of the enormous energy that we know to exist within the nucleus, but about which we now know too little even to make a guess as to how it may influence our present theories.

INDEX

E

F

G

I

R

V

W

X

Y

Z